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Special Issue Reprint

Regional Sustainable Development of Yangtze River Delta, China

Edited by
Wei Sun, Zhaoyuan Yu, Kun Yu, Weiyang Zhang and Jiawei Wu

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Review

Regional Integration and Sustainable Development in the Yangtze River Delta, China: Towards a Conceptual Framework and Research Agenda

Jiawei Wu and Wei Sun *

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Abstract: Understanding the interactions between the human sphere and the natural sphere in key places and regions of the world is crucial for promoting sustainability science and achieving sustainable development. As one of the emerging global city-regions in China and the Global South, the Yangtze River Delta (YRD) plays an increasingly nonnegligible role in the globalized economy and telecoupling social-ecological systems (SESs). Considering the well-known importance and representativeness, the YRD has been regarded as an appropriate experimental site of integrated research on geographical and sustainability science at the subnational scale. This paper tries to establish theoretical and practical linkages between regional integration and sustainable development at the subnational scale based on the sustainable development goals (SDGs), the Chinese contexts, and a literature review of relevant researches. We argue that future research should pay more attention to the interdisciplinary, transregional, and multi-scale attributes of issues related to regional integrated and sustainable development in the YRD. The following research agendas, such as linking SDGs to regional integrative development, analyzing the sustainability of regional SESs, assessing the integrated region at the subnational scale, investigating the YRD at different geographical scales, exploring applicable governance structures and institutions, as well as applying multi-source data and interdisciplinary methodologies, call for more scholarly attention. We hope that this paper could be an initial motion to expand and enrich relevant research.

Keywords: regional sustainable development; social and ecological systems; regional integration; research agendas; SDGs; China

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1. Introduction

The world as a whole has been facing increased crises on multiple fronts, including climate change, economic recession, food and energy security, territorial conflicts, and public health emergencies [1,2]. Achieving sustainable development has increasingly become a global consensus; however, how to promote sustainable development has always been a thorny issue for policymakers around the world [2–4]. In 2015, the United Nations (UN) proposed the Sustainable Development Goals (SDGs), which were designed to find an effective path out for promoting sustainable development by dealing with the limited problems related to socioeconomic development, eco-environmental protection, and human well-being until 2030 [5,6]. SDGs and evaluation indicators from 17 aspects provide an action plan for sustainable development practices at different geographical scales, and the achieving trajectories and processes have attracted extensive attention from scholars of multiple disciplines [7–10]. Relevant research has profoundly facilitated the advances in theories, methodologies, and policy implications of sustainability science [11,12].

The concept of sustainable development, which is well-known but somewhat ambiguous, has gradually entered the literature on economic growth, eco-environmental evolution, and public policy since the release of the Brundtland report (titled "Our Common Future") and global Agenda 21 in the 1980s/1990s [13–15]. Particularly, sustainability science emerged as a new research field focusing on the interactive dynamics between natural and social systems across the full range of scales from local to global, and on how to form effective sustainable trajectories and adaptive governance frameworks to deal with the wide spectrum of challenges [16,17]. The regional character of research topics in sustainability science calls for more scholarly efforts in the long-term interdisciplinary investigation on nature–society (or social–ecological) interactions in specific regions with different territorial functions [16]. A large body of literature also indicated that examining the features, processes, and outcomes of social–ecological interactions in key places and regions of the world is still important for sustainable practices and achieving SDGs at the global scale [18–20].

As one of the largest developing and emerging economies around the world, China has been a strong advocate and practitioner of sustainable development since the implementation of "China's Agenda 21" in 1994 [21,22]. However, the high-growth, resource-intensive, and export-oriented developmental trajectory that China pursued before the 2010s, as well as the relatively small resource amount per capita and the spatiotemporally uneven eco-environmental status, have sharpened the contradiction between human activities and ecosystems across the country [23,24]. This makes the developmental transition under the guidance of SDGs even more pressing in China [25–27], just as any other developing country is facing. Furthermore, considering the decisive role played by intensive human activities related to rapid industrialization and urbanization in eco-environmental changes in the Anthropocene Epoch [28], it is essential to further examine the interactions between nature and society in highly urbanized and ecologically sensitive regions around the world.

Therefore, the basis of our discussions is the importance of research on nature–society (or social–ecological) interactions and sustainable development practices at the subnational scale (e.g., highly urbanized regions located in the Global South and developing countries) for sustainability science and achieving SDGs. Following similar research veins, variegated issues related to economic, social, and eco-environmental sustainability in China's major urban agglomerations, such as the Beijing–Tianjin–Hebei region (JJJ), the Yangtze River Delta (YRD), the Pearl River Delta (PRD), and the Chengdu–Chongqing economic circle (CY) region, have received much scholarly attention in multiple (inter)disciplines [29–34]. These urban agglomerations are key regions for regional integration and sustainable development in China. However, existing studies on the integrated or collaborative path to regional sustainable development, as well as the achievement of SDGs and the sustainability of social–ecological systems (SESs) at the regional scale, are quite limited. Focusing on the YRD, which is one of the national urban agglomerations in China and one of the emerging global city-regions in the Global South, this paper considers two interrelated objectives. On the one hand, this paper tries to develop a conceptual framework for building linkages between regional integrated collaboration and the promotion of regional sustainable development, with particular attention given to the nexus between SDGs and regional integrated development tasks. On the other hand, this paper tries to propose future research agendas related to regional integration and sustainable development of the YRD, especially issues related to the achievement of SDGs, regional SESs, and integrated regions at the subnational scale.

The remainder of this paper is arranged as follows. Section 2 introduces the development situation and representativeness of the YRD. Section 3 reviews and summarizes the literature on regional integrative and sustainable development in the YRD from geographical and human–environment interactive perspectives. Section 4 presents our conceptual framework and future research agendas. Then, we conclude and discuss in the end.

2. Developmental Situation and Representativeness of the YRD

According to "the outline of the regional integrated development plan of the YRD" issued by the CPC Central Committee and China's State Council, the YRD includes four province-level regions (i.e., Shanghai, Jiangsu, Zhejiang, and Anhui). Located in eastern coastal China (see Figure 1), the YRD has been regarded as the pioneer and frontier of China's reform and opening-up, as well as the epitome of China's industrialization and urbanization, since the late 1970s [35–37]. Moreover, the YRD has become one of the most developed regions, with the highest socioeconomic levels through rapid growth over the past half-century, contributing to the Chinese path to modernization and national rejuvenation [38]. The YRD carries 16.74% of China's population, 24.14% of China's GDP, and 14.59% of China's fiscal revenue, with only 3.7% of China's territory in 2021. The USD 4.28 trillion GDP of the YRD in 2021 also exceeded that of most developed economies such as Germany, the United Kingdom, and France. The proportion of the urban population of Shanghai, Jiangsu, Zhejiang, and Anhui, respectively, reached 89.30%, 73.94%, 72.70%, and 59.39%. The positions and roles of Shanghai, one of the recognized global cities, and other regional hubs (e.g., Nanjing, Hangzhou, Suzhou, Wuxi, Ningbo, and Hefei) of the YRD in the world city network and the globalized economy have been increasingly prominent [39,40]. The YRD has become an emerging global city-region led by Shanghai.

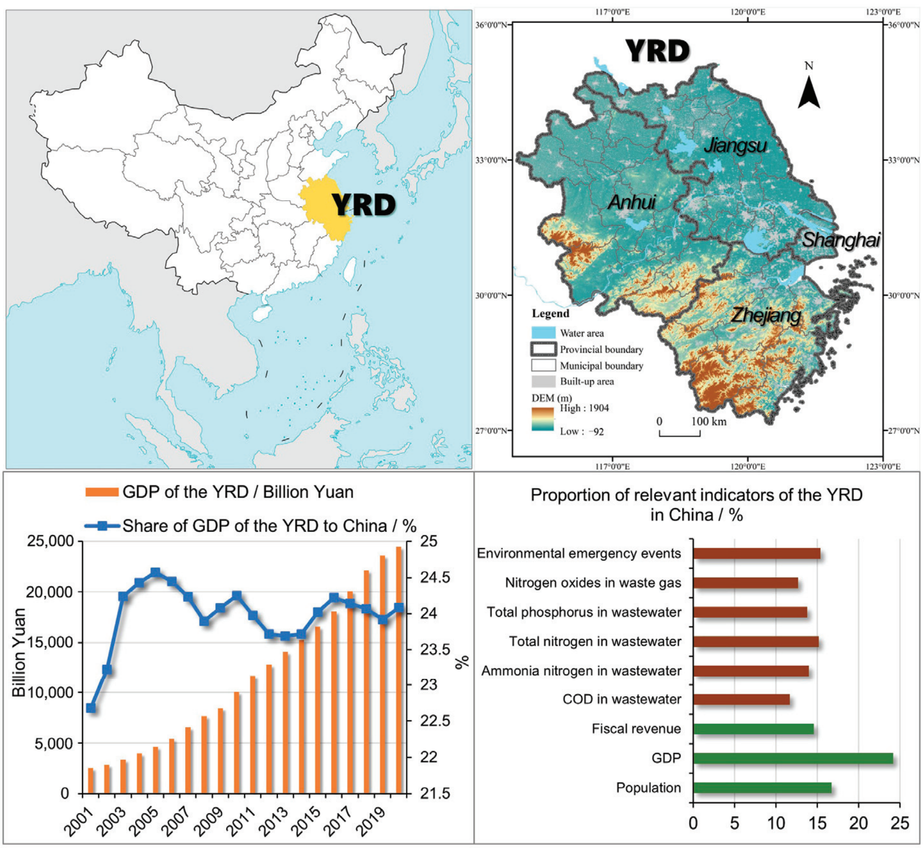

Figure 1. Geographical location and socioeconomic overview of the YRD.

With regard to the natural sphere or eco-environmental status, the YRD is composed of an estuary delta plain and surrounding hilly areas, resulting in relatively lower regional average elevation and slope. Located in the lower reaches of the Yangtze River, Huaihe River, Qiantang River, and ancient Yellow River, the YRD features variegated river–lake systems and abundant water resources. Moreover, the main climate type in the YRD is subtropical monsoon, characterized by warmth and humidity. The aforementioned conditions related to climate, topography, and natural resource endowment are conducive to highly intensive urban development and industrial agglomeration in the YRD. However, the intensive exploitation and extensive utilization of natural resources (e.g., land, non-renewable energy, and mineral resources) have brought great pressure to the limited capacity of the regional ecological environment in the YRD [41–43]. The YRD, accounting for 15.1% of total nitrogen emissions, 13.8% of total phosphorus emissions, 12.7% of nitrogen oxides emissions, and 15.4% of environmental emergency events in China in 2020, has been viewed as one of the regions with the most serious industrial pollution across the country. This led to an investment of RMB 13.7 billion in the treatment of industrial pollution in the YRD, accounting for 30.2% of China. The contradiction between socioeconomic development and eco-environmental protection has been becoming increasingly acute in the YRD, especially in ecologically sensitive subregions.

Since the early 2010s, China has been promoting the trajectorial transition from the high-growth, resource- and pollution-intensive development mode to the high-quality, innovation- and green-oriented one [23,44,45]. A more prominent contradiction presented by the human–environment or social–ecological systems has forced local governments in the YRD to pursue the transition of developmental trajectories earlier. The YRD tends to be regarded as the pioneer in taking a trajectory for regional transition and sustainable development [36,46,47], namely, a harmonious development mode between human activities and the eco-environment in China. However, considering unbalanced regional socioeconomic development and eco-environmental status, as well as the division of administrative regions and local protectionism [35,37], it needs unified visions, place-tailored strategies, and integrative actions to promote sustainable development of the YRD. Interregional cooperation in industrial transition, technological innovation, infrastructure construction, and public services and policies should be key to achieving sustainable development of the YRD. Moreover, how to deal with regional inequalities at the economic level, eco-environmental quality, and social welfare are also important issues faced by the YRD in facilitating regional integration and sustainable development.

To sum up, as an emerging global city-region, the YRD will play an increasingly vital role in stimulating economic growth and addressing climate change in China and even the world. Located in the lower reaches of the Yangtze River, the YRD is a typical estuary delta with low mountains (hills) and variegated river systems. The complex or diverse ecosystems and territorial functions in the YRD have been largely affected by rapid urbanization and industrialization, as well as other intensive human activities. This brings about a series of problems, including eco-environmental degeneration, regional inequality, and homogeneous competition, that need to be solved for regional sustainable development in the YRD. "Regional high-quality-oriented and integrative development in the YRD" has become one of the national regional strategies in China since 2018. We argue that the development mode and predicaments of the YRD are representative of emerging economies, and the evidence of social–ecological interactions and the practices of sustainable development in the YRD can serve as a strong reference for China and other developing economies in the Global South.

3. Literature Review under Geographical and Sustainable Perspectives

Considering the aforementioned importance and representativeness of the YRD, critical issues related to economic restructuring, urbanization, eco-environmental changes, and collaborative governance in the YRD have been profoundly examined by scholars from various disciplines. In order to develop a conceptual framework for research on regional integration and sustainable development in the YRD, our literature review focuses on the seminal works and impressive findings based on geographical, sustainable development, or human–environment interactive perspectives. We mainly conclude the relevant research hotpots and main signs of progress from the following aspects.

3.1. Industrial Restructuring, Technical Innovation, and Economic Growth

Industrial restructuring and technical progress in the YRD, as well as its impact on China's economic transition and the globalized economy, have received much scholarly attention [34,48,49]. Since China's reform and opening-up in 1978, the industrial development of the YRD has long been featured as township- and village-owned industries, export-oriented industrialization, and footloose foreign direct investment (FDI), which are respectively known as the Sunan model, the Wenzhou model, and the development-zone fevers in the literature [50–54]. With the increased pressure on economic efficiency and environmental protection, local governments in the YRD have been increasingly promoting industrial transformation oriented to producer services, advanced manufacturing, and high-tech and knowledge-intensive industries during the past two decades [34,36]. Scholars and policymakers put more emphasis on the role played by entrepreneurship and technical innovation in industrial transformation and spatial relocation in the YRD [55,56]. Existing studies have indicated that knowledge-intensive industries and relevant innovative activities are largely concentrated in major cities and the core YRD (e.g., Shanghai, southern Jiangsu, and northern Zhejiang), while traditional and low-end manufacturing industries are gradually transferred to the peripheral YRD [57–60]. Research also signified that industrial distribution and its changing trends might vary across different sectors in the YRD [36,57].

In addition, the continuous upgrading and relocation of various industries have profoundly shaped the regional division of labor in the YRD [38,59,61–63]. Major cities such as Shanghai, Nanjing, Hangzhou, Suzhou, and Hefei largely act as gathering centers of high-end industries and innovative activities. Cities and counties along the Yangtze River and coastline, as well as various development zones, are the gathering places of advanced manufacturing. The peripheral regions (e.g., northern Jiangsu, southwestern Zhejiang, and northern and southern Anhui), as well as counties around major cities, tend to have advantages in undertaking industrial transfer and promoting the agglomeration of green- and ecologically oriented industries (e.g., ecotourism and eco-agriculture).

3.2. Urbanization, Urban System, and Urban–Rural Relations

The proportion of the urban population in the YRD has increased from 43.01% in 2000 to 60.33% in 2011 and 70.85% in 2020. Such a rapid urbanization process accompanied by large-scale construction of urban infrastructure and public utilities has aroused widespread concern among scholars [64–66]. Existing studies have comprehensively investigated spatiotemporal variations and driving forces of the urbanization process in the YRD [67,68]. With the spatial agglomeration of industries and population, as well as the excessive reliance on land revenue, the urbanized or built-up areas in the YRD have experienced rapid expansion since the 1990s [69–71]. The urban built environment, infrastructure, and living convenience have been greatly improved in the YRD; however, urban sprawl or the traditional mode of urbanization also brought a series of problems such as inefficient land use, job–housing imbalance, unaffordable housing, unequal welfare, and eco-environmental degeneration [71–74]. Under the guidance of the national strategy of new-type or people-centered urbanization, the speed of urban expansion in the YRD has slowed down since the early 2010s. More attention has been paid to the quality of urbanization, especially equal access to high-quality public services for all urban and rural residents [64]. Research has also implied that the level and quality of urbanization significantly differ across regions, for instance, urbanization in Shanghai, southern Jiangsu, and northeastern Zhejiang presented better performance [65].

The restructuring of urban hierarchies and networked connections in the YRD has also been the subject of empirical research [75–77]. The literature illustrated that, with the improvement of transportation and information infrastructure networks, socioeconomic exchanges and element flows among cities in the YRD have been increasingly closer [78,79]. Meanwhile, there exist significant differences between cities in the attractiveness and carrying capacity of high-end productive factors, industries, and services in the YRD due to urban disparities in administrative levels, geographical locations, resource endowments, and agglomeration economies [58,75]. Major cities, such as Shanghai, Nanjing, and Hangzhou, tend to occupy leading positions in urban networks related to various inter-city relations (e.g., population mobility, traffic flow, and corporate linkages) [63,80,81]. Existing studies, therefore, have mapped a significant "core–periphery" network structure, in which Shanghai and regional hubs dominate inter-city relations and urban hierarchies in the YRD, marginalizing the middle-sized and small cities or counties located in the peripheral regions [77,82].

The urban system features of being networked, polycentric, and asymmetric in the YRD facilitated inter-city linkages and collaboration on the one hand, and strengthened the spatial polarization effects of major cities on the other hand. For instance, scholars found that job opportunities, better-built environment, and high-quality public services and amenities tend to concentrate in a few metropolises and urban districts [35]. Issues related to urban social spaces, including housing, rural–urban migration, and public welfare in the YRD have been widely discussed in the literature [73,81,83,84]. In addition, the rapid industrialization and urbanization processes have also triggered researchers' thinking on research topics associated with urban–rural relations and the territorial functions of rural areas. The potential trajectories to restructure the urban–rural dual structure, and then achieve rural revitalization and sustainable development, have become new hotspots in empirical research on the YRD [85,86].

3.3. Natural Resource Utilization and Eco-Environmental Changes

The basal characteristics and human utilization of various natural resources in the YRD have been widely investigated in the existing studies [69,87,88]. Spatiotemporal heterogeneities of natural resource use forms, use efficiency, and management systems in the YRD have become topics of common concern [70,89]. With the socioeconomic transition, the natural resource utilization mode has transformed from irrational and extensive to economical and intensive in the YRD, largely resulting in continuous changes in the scale, structure, and spatial pattern of natural resources. Existing studies also documented that natural resource use efficiency, which could be measured by economic output or eco-environmental consequences, in the YRD has been increasingly improving, although efficiency differences between sub-regions, provinces, cities, or counties are still obvious [90,91]. Take land resource as an instance; the transformation from the natural surface or cultivated land to construction land is the main manifestation of land use transition or land cover change in the YRD due to rapid industrialization and urbanization [92]. Urban or construction land use efficiency, which could be affected by multiple factors including technical progress, industrial structure, policy setting, and ecosystem constraint, might present a better performance in the core YRD and relevant central cities [71]. The renovation of the land management system oriented by rational, intensive, and efficient utilization in the YRD has also attracted much scholarly attention [93].

The extensive and ineffective utilization of natural resources, which are associated with traditional trajectories of industrialization and urbanization, has led to serious ecological damage and environmental pollution in the YRD over a long period. Existing studies have adequately examined spatiotemporal variations of air pollution (quality), water pollution (quality), soil pollution, solid waste pollution, and emission patterns of various contaminants (e.g., PM2.5, COD, NH_3-N, and industrial sulfur dioxide and wastewater) in the YRD [94–97]. With economic transition and the strengthening of environmental regulations, the eco-environmental quality in the YRD has gradually improved; however, pollution problems in some areas or territorial types, including lake basins, coastal zones, riverside areas, and hilly areas, are still precarious and intractable. Furthermore, environmental problems related to greenhouse gas emissions (e.g., CO_2 emissions), urban heat islands, and extreme weather in the YRD against the background of global climate change have received increasing scholarly attention [72,98–100].

The over-exploitation of natural resources and severe environmental pollution caused by human activities have profoundly threatened ecosystems and relevant service functions in the YRD. The contradiction between the rapid socioeconomic development and the limited resources and environmental carrying capacity can be widely observed in the YRD [41,101]. The existing literature suggests that ecosystem services such as resource abundance, climate comfort, soil conservation, and environmental self-purification have been degraded, and present significant regional disparities in the YRD [102–104]. This forces the central and local governments in China to pay more attention to ecosystem restoration and the improvement of ecological functions in the YRD. According to "the plan for the joint-protection of the eco-environment of the YRD", regions with higher ecological importance and service function, such as Yangtze River, Huaihe River, Taihu Lake, and Hongze Lake, as well as hilly areas in western Anhui, southern Anhui, southern Zhejiang, and western Zhejiang, have been highlighted in the planned pattern of ecological security in the YRD.

3.4. Interregional Cooperation and Collaborative Governance

The YRD, which is different from integrated regions across national borders (e.g., EU and NAFTA) or city-regions located within a single subnational administrative area (e.g., the PRD), is a trans-provincial mega-city-region with a long history of region-building and integrative experiments in China [105]. Based on the theoretical perspective of China's city-regionalism, existing studies focused on the region-building process and the changing governance structure in the YRD since the early 1990s [106,107]. Scholars elaborated that the integrated development of the YRD might be driven by the synergy of governmental intervention and market forces [35,108]. On the one hand, a series of regional plans and supporting policies issued by the Chinese central government, which could be viewed as a top-down process dominated by the state, largely promoted regional identity and integration of the YRD [105]. On the other hand, various interregional collaborations have been initiated by local governments, which are the main feature of the bottom-up mechanism of regional integration of the YRD, to implement national strategies and handle trans-administrative affairs [109–111]. Moreover, with increased marketization, the weakening of local protectionism has greatly facilitated enterprise investment and population migration across administrative boundaries within the YRD. These forces, derived from the market and individuals, matter more for regional integration, making the YRD different from other trans-provincial mega-city-regions (e.g., the JJJ) in China.

Considering the challenges and tasks of regional integrative development, existing studies have widely discussed the processes, modes, and consequences of interregional cooperation related to various trans-administrative affairs in the YRD [61,108,110]. Especially, interregional cooperation within fields such as industrial relocation, collaborative innovation, infrastructure construction, and eco-environmental protection, has attracted much scholarly attention. For instance, in addition to interregional enterprise investment and relocation, cooperative construction and operation of industrial districts or high-tech parks have been the main measurement of regional city-to-city cooperation in the YRD [112–114]. Scholars tend to investigate collaborative innovation in the YRD from the perspective of the spatial transfer and off-site commercialization of valuable patents [115,116]. Some studies have been designed to examine driving mechanisms, and the role played by multilevel governments and market entities, in the construction of cross-regional transport infrastructure [117]. Furthermore, aiming at addressing interregional or watershed eco-environmental problems, regulatory systems, and policy settings (e.g., the interregional river or lake chief system) involving different local governments in the YRD have gradually become research hotspots [111,118].

In sum, existing studies and relevant findings have largely advanced our understanding of the spatiotemporal heterogeneities and changing dynamics of various aspects related to socioeconomic, eco-environmental, and institutional systems in the YRD. The literature has also indicated increasing interest in complex relationships or interactive dynamics between the human sphere and the natural sphere from the perspective of social–ecological systems [41,43,92]. Particularly, extensive empirical investigations of eco-environmental changes in the YRD have underlined the adaptation and feedback of ecosystems under the influences of human activities [43,47]; Meanwhile, urban expansion, industrial (re)distribution, and regional development strategies in the YRD would be profoundly affected by place-specific ecosystems and institutional contexts of eco-environmental protection [71]. To better understand and promote regional high-quality-oriented, integrative, and sustainable development in the YRD; however, the existing studies may have the following limitations or less concerning issues: First, while interregional linkages and cooperations have attracted considerable attention from scholars, few theoretical and empirical researches have discussed the measurement (or assessment) and driving mechanisms of regional integrated development in the YRD. Second, the timely and comprehensive investigation of sustainable development practices, especially the achievement of different SDGs at the regional or urban level, in the YRD has been largely neglected in the literature. Third, existing studies on a single socioeconomic, eco-environmental, or governing phenomenon, as well as a single productive element or natural resource, are extensive, while interdisciplinary researches on the complex human–environmental systems or SESs in the YRD are quite limited. Fourth, little scholarly attention has been paid to transitional or sustainable trajectories of the YRD under the new global context and challenges, especially climate change, COVID-19, anti-globalization, and territorial conflicts.

4. Conceptual Framework and Research Agenda

To fill the aforementioned research gaps and then promote regional development more effectively in the YRD, one key question we need to answer is how to make a causal association between integration and sustainable development at the subnational scale (or in a trans-administrative mega-city-region). Regional integration at the subnational scale can be regarded as the process of interregional division of labor and collaboration based on common benefits, attitudes, actions, and expectations [38,111]. The cruxes of this process might be the consensus, joint action, and systematic consideration among different places (e.g., developed and developing regions), fields (e.g., social, economic, and eco-environmental issues), and agents (e.g., governments, market entities, NGOs, and the public), which are also the main challenges to be overcome to accelerate the simultaneous implementation or achievement of the full set of SDGs [3,4,119]. We argue that the implementation, assessment, and realization of 17 SDGs, as well as sustainable development practices, at the subnational scale should be placed in the process of regional integration. By highlighting the shared visions, multi-dimensional synergies, interregional cooperation, stakeholders' joint-action, institutional reformation, and mission-oriented and place-based policies, the process of regional integrative development could be an effective strategy or approach to achieve sustainable development at the subnational scale (see Figure 2). Following this vein, we try to match 17 SDGs with major tasks of regional integration documented in "the outline of the regional integrated development plan of the YRD" (see Table 1).

Table 1. The association between 17 SDGs and major tasks of regional integrative development in the YRD.

Major Tasks of Regional Integrative Development in the YRD		Relevant SDGs
Task Categories	**Task Definitions (or Contents)**	
Promoting a new pattern of regional coordinated development	Strengthening regional division of labor and cooperation Accelerating integrative development in metropolitan areas Promoting urban-rural integrated development Promoting joint development of transboundary regions	SDG10: Reducing inequality SDG11: Sustainable cities

Table 1. *Cont.*

Major Tasks of Regional Integrative Development in the YRD		Relevant SDGs
Task Categories	**Task Definitions (or Contents)**	
Establishing a regional system of industrial cooperation and collaborative innovation	Building regional innovation communities Promoting interregional industrial division and cooperation Facilitating the integration of industry and technical innovation	SDG1: No poverty SDG8: Decent job SDG12: Responsible consumption and production
Improving infrastructure connectivity	Building regional transportation systems Building the digital YRD Advancing trans-regional energy infrastructure Improving inter-provincial water conservancy projects	SDG6: Clean water SDG7: Clean energy SDG9: Infrastructure SDG11: Sustainable cities
Strengthening joint protection of eco-environmental system	Jointly strengthening ecological protection Promoting coordinated environmental prevention and pollution control Promoting coordinated eco-environmental regulation	SDG6: Clean water SDG13: Climate action SDG14: Life below water SDG15: Life on land
Facilitating public services sharing	Promoting standardization and facilitation of public services Sharing high-quality education and medical services	SDG1: No poverty SDG2: Zero hungry SDG3: Health and well-being SDG4: Quality education
	Promoting regional cooperation in cultural tourism	SDG12: Responsible consumption and production
	Jointly building a fair and inclusive social environment	SDG5: Gender equality SDG16: Inclusive society
Promoting high-level and coordinated opening-up	Jointly building advanced opening-up platforms Deepening opening-up in key fields and regions Jointly building a world-class business environment	SDG12: Responsible consumption and production SDG17: Global partnerships
Reforming institutional setting for regional integration	Establishing an institutional system with unified rules Promoting regional integration of factor markets Improving regional collaborative mechanisms at multi-levels and in various fields	SDG10: Reducing inequality SDG17: Global partnerships
Building a demonstration zone of green and integrated ecological development	Creating a regional model for eco-friendly integrated development Innovating the institution for integrated development in key fields Strengthening the integration and innovation of reform approaches	SDG6: Clean water SDG10: Reducing inequality SDG13: Climate action SDG14: Life below water SDG15: Life on land
Building the new functional area of China (Shanghai) Pilot Free Trade Zone	Building pilot free trade zones at a higher level Promoting investment/trade liberalization and facilitation Improving supporting institutions and supervision systems Driving a new round of reform and opening up in the YRD	SDG12: Responsible consumption and production SDG17: Global partnerships

Note: Major tasks of regional integration in the YRD were documented in "the outline of the regional integrated development plan of the YRD".

In addition, to better understand and unravel complex nexuses between regional integration and regional sustainable development, it is essential to conduct an in-depth and interdisciplinary analysis of the human sphere (socioeconomic development and institutional context), the natural sphere (eco-environmental system), and interactive mechanisms between the two in and out of the YRD. Considering interdisciplinary, transregional, and multi-scale attributes of issues related to regional integrative development and SDGs achievement, as well as the challenges and tasks faced by regional integration of the YRD after it rose to one of the national regional strategies in China, future trends and research agendas could be derived from the following aspects: the synergistic achievement of regional integration and SDGs; the analysis of the sustainability of regional SESs; noteworthy issues considering multiple geographical scales; the innovation in governance structure and institutional setting; and the support or application of big data and new methodologies.

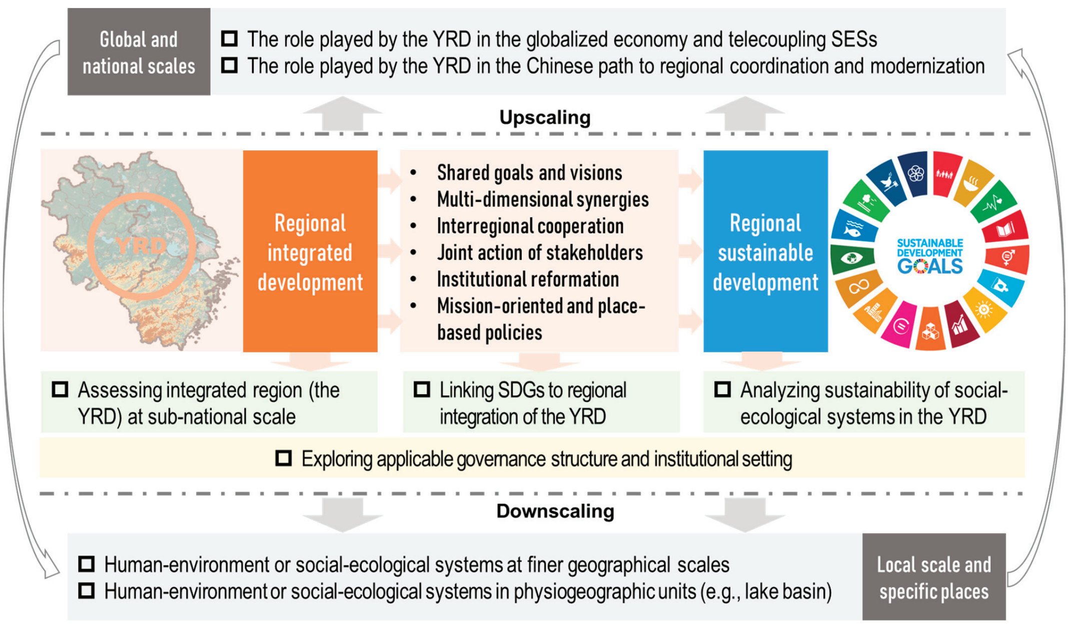

Figure 2. Conceptual framework and research agendas of regional integrated and sustainable development in the YRD.

4.1. Linking SDGs to Regional Integration of the YRD

The assessment of SDGs achievement and the measurement of individual SDG indicators have been widely examined in extensive literature since the UN released the SDGs (including 17 goals and 169 targets) in 2015 [6,120]. In addition to the global scale, the key to implementing and achieving SDGs, as well as sustainable development practices guided by SDGs, at the national, regional, or local scale, has attracted much scholarly attention [8,25]. Based on the Chinese context, seminal works have discussed comprehensively and in-depth the classification, measurement, and achievement of strategies and approaches of SDGs at the national and provincial scales, especially the complex interactions, synergies, and trade-offs among the 17 SDGs [3,4,25]. However, empirical researches on achieving SDGs in trans-administrative regions (e.g., mega-city-regions, urban agglomerations, and metropolitan areas) in China are thin on the ground.

"The outline of the regional integrated development plan of the YRD" issued by the CPC Central Committee and China's State Council has specified the objectives and tasks of regional coordination, industrial transformation, cross-border infrastructure, eco-environmental protection, social welfare, opening up, and institutional reform for the YRD in the coming 15 years (see Table 1). How to promote and then achieve these visions has attracted extensive attention from policymakers and scholars. Existing studies indicated that promoting economic agglomeration, social equity, and ecological security, which are consistent with the main dimensions of SDGs, might be the keys to achieving integrated development in the YRD [38]. Moreover, there is a consensus that promoting and achieving socioeconomic and eco-environmental sustainability are the ultimate goals of integrative development in the YRD. We argue that the implementation of planning tasks and the achievement of the 17 SDGs should and could be synchronized in the YRD. Linking the full set of SDGs and the approaches to their achievement to the process of regional integration in the YRD deserves more scholarly attention.

The following issues should be of concern in future research: First, considering limitations on regional and local data availability, comprehensive and applicative assessment frameworks of regional sustainable development in the YRD should be developed on the basis of the broad content and detailed indicators of the SDGs. Second, the degree of achievement of the 17 SDGs (or specific indicators) and their regional differences, as well as the driving mechanism behind relevant results, should be measured and discussed by future research. Third, to achieve sustainable development in an integrated pathway in the YRD, the interactions among different SDGs and interregional achievement synergy need more scholarly attention. Furthermore, future research needs to further uncover the relations between the SDGs contents and integrated development tasks in the YRD, and then find the key to promoting joint action by local governments and various departments through top-down and collaborative governance.

4.2. Analyzing Sustainability of Social–Ecological Systems in the YRD

The harmony (or balance) between the human sphere and the natural sphere, namely the stability of our integrated nature–society system, is both an important foundation and the ultimate goal of regional integration and sustainable development in the YRD. A large body of literature has suggested that the framework of SESs could be an effective perspective and analytical tool for sustainable development issues [121–123]. According to the framework developed by Ostrom (2009), SESs are composed of various subsystems, including resource systems, resource units, users, social, economic, and political settings, related ecosystems, mutual interactions, and outcomes [121]. Similar to the regional character of research topics in sustainability science, some scholars have illustrated that a better understanding of the SESs framework and relevant concepts or theories, such as resilience, adaptability, and transformability [124], need to be based on complex contexts of specific scales and places [20,125,126]. The literature implied increasing interest in the multi-scale and cross-scale assessment of SESs, as well as SESs of regions with special territorial functions (e.g., plateau, watershed, and urban agglomerations) [18,19,126–128].

Focusing on simplified subsystems of SESs, as well as the interactive dynamics between specific subsystems or individual variables (e.g., urbanization and land use change), existing studies on human–environment systems or SESs in the YRD are slightly fragmented. Researches on evolutionary dynamics and feedback mechanisms of complex coupled SESs in the YRD are quite limited. This situation is inconsistent with the intensified contradiction between human activities and eco-environmental systems, as well as regional disparities in territorial functions and social–ecological importance, within the YRD. We argue that deepening the examination of the evolutionary processes and feedback mechanisms of the coupled SESs and then generating policies tuned to place-specific conditions are the main requirements of the human–environmental equilibrium and sustainable development in the YRD.

The following issues call for more scholarly attention: First, the research application of theoretical conceptions such as resilience, adaptability, and transformability, as well as the evolutionary dynamics, feedback mechanisms, and regime shifts of SESs and relevant subsystems in the YRD should be in the center of future research. Second, the dynamics and sustainability of SESs in the YRD's subregions with special territorial functions (e.g., Yangtze River Basin, Taihu Basin, Jianghuai Plain, hilly and mountain areas, and estuarine and coastal regions) deserve more empirical investigations. Third, critical issues related to the feedback mechanism of SESs, including land cover change, ecosystem services, the water–energy–food nexus, environmental economic geography, as well as the coupling mechanism between urbanization and eco-environmental systems, deserve more scholarly investigations.

4.3. Assessing Integrated Region at Subnational Scale

The essence of regional integration both at the supranational scale and the subnational scale is to achieve interregional economic convergence and welfare equilibrium by breaking administrative barriers, weakening local protectionism, and promoting cross-border factor mobility. The single market and customs union without national borders, as well as the Eurozone or monetary integration, are the prominent features or achievements of the EU, which is a well-known integrated region at the supranational scale [129]. The social, cultural, and institutional contexts of the YRD, a trans-provincial integrative region at the subnational scale, are significantly distinct from the EU. Although different provinces, cities, and counties in the YRD have the same official currency, language, and taxation system, the fiscal decentralization and the performance appraisal of officials in China have largely led to regional competition and local protectionism across the country. Without state intervention and the top-down directives from the Chinese central government, local governments and officials tend to value local socioeconomic development more, rather than trans-administrative public affairs within the YRD. Existing studies have examined interregional corporate linkages, technical cooperation, and population mobility, suggesting that national plans and policies related to integrative development play an increasingly positive role in eliminating administrative division and promoting regional equality in the YRD [38,105,107]. However, it is difficult to have an insight into the overall picture of the integrative development process in the YRD from research based on specific issues.

The driving mechanisms, achievement approaches, and evaluative criteria of regional integration in the YRD and other integrative regions at the subnational scale call for more scholarly investigations. First, a more general theoretical framework, which can comprehensively uncover the motivations, actions, and roles of different stakeholders (e.g., individual enterprises, multi-level governments, the public, and NGOs) and their gaming relations associated with cross-border affairs and regional integration, should be developed for the YRD. Second, more empirical research should be designed to better understand the synergies among different realms, such as industrial collaboration, eco-environmental protection, infrastructure connectivity, and public services sharing, which are crucial for roundly promoting regional integrated development in an orderly fashion. Third, developmental orientations, industrial or innovative directions, and transitional trajectories of regions with different development bases and stages in the YRD should be further discussed in future research, especially based on theoretical perspectives such as smart specialization and spatial division of labor. Fourth, a results-oriented assessment system and relevant appraisable indicators should be developed to identify the propulsion phases and achievements of regional integration in the YRD. Evaluating indicators of regional integration in the YRD could include but are not limited to dimensions such as density, distance, efficiency, and specialization and division. In addition, some new ways of interregional collaboration, such as innovation enclaves, industrial chain alliances, and the joint development of transboundary regions, deserve more scholarly attention.

4.4. Investigating the YRD at Different Geographical Scales

On the one hand, theoretical and empirical studies on the YRD, which is an emerging global city-region deeply embedded in the global nature–society system, and the strategic layout of China’s reform and opening-up, should be placed under the context of increased globalization and transitional China. On the other hand, the YRD is composed of different administrative areas (e.g., province-, city-, or county-level) and territorial types (e.g., plain, hills, and lake basin), so future research should pay more attention to special features of various administrative levels and physical geographic units in the YRD. Differences between geographical scales within the YRD have been widely discussed in existing studies on topics related to socioeconomic linkages and eco-environmental changes. More detailed research on the interactions of geographical scales, particularly the role and position of the YRD within the nature–society system at the global or national scale, is also needed in the future.

First, the development practices, crisis countermeasures, and notable contributions of the YRD in the processes of economic globalization and global climate change call for more scholarly investigations. For instance, future research needs to focus on how the cities or enterprises located in the YRD engage in and affect the international trade system, the world city network, and the global production network. Based on the integrated framework of telecoupling [130], the examination of the interactions between distant coupled human and eco-environmental systems including the YRD may be an important and interesting issue in future research. Second, the role played by the YRD, one of the urban agglomerations with the highest level of socioeconomic development, in the economic transition, regional collaboration, and sustainable practice of China deserves empirical research. In particular, comparative studies of the YRD and other urban agglomerations (e.g., the JJJ and PRD) in China, as well as the radiation and spillover effects of the YRD on the Yangtze River Economic Belt and inland regions of China, call for more scholarly attention. Third, more effort should be made to examine socioeconomic statuses, eco-environmental changes, urban–rural relations, and human–environment systems at a finer geographical scale (e.g., township, village, and gridded units), as well as in physical geographic units (e.g., lake basins and hilly regions).

4.5. Exploring Applicable Governance Structure and Institutional Setting

Existing studies have signified that promoting regional integration or dealing with trans-administrative affairs requires a good balance between multi-level governments, different local authorities, as well as the government, the market, and the public [111]. Moreover, regional disparities in economic level, factor endowment, and eco-environmental conditions determine that one-size-fits-all regional development policies are not feasible in the YRD. To optimize the institutional setting and support policies of integrative development of the YRD, applicable governance structures and policy instruments related to interregional cooperation and synergetic growth need more scholarly attention.

Future research could focus on the following aspects: First, orientations of institutional reforms, especially the specific approach to establishing an intergovernmental consultation platform and a trans-administrative integrated market, need to be deeply discussed to weaken the negative impacts of administrative division in the YRD. The governance structure and maintaining mechanism of intergovernmental cooperation based on cost-, risk-, and benefit-sharing principles should be at the center of relevant research. Second, regional policy instruments and implementation standards should be determined according to the actual situation of specific places and issues; mission-oriented and place-based policies matter more to regional integration. More empirical studies should be conducted to support the assessment of existing regional development policies related to industrial cultivation, technical innovation, and eco-environmental regulation, as well as their impacts on socioeconomic development and ecosystems, within the YRD. Third, the potential trajectories and policy implications of adaptive, transformative, and collaborative governance for the sustainability of SESs and the realization of sustainable development (or SDGs) in the YRD call for more studies. In addition, the experience generalization and demonstration effect of integrated development practices in a few fields (e.g., free trade, systematic innovation, and ecological compensation) and regions (e.g., demonstration zone of green and integrated ecological development of the YRD) deserve tracking and further examination.

4.6. Applying Multi-Source Data and New Methodologies

The aforementioned research agendas need more empirical investigations based on the interactions between multiple domains, regions, and spatial scales, and this generates new requirements for research materials, data, and methods. The data widely used in existing studies, such as attribute data of specific regions, as well as statistical data and published materials based on administrative divisions, are difficult to support research on the sustainability of SESs, the achievement of SDGs, and interregional synergies. With regard to data collection and processing, future research should pay more attention to the application of socioeconomic big data based on individual and corporate attributes, as well as multi-source geospatial data based on the virtual constellation and cloud computing. According to the features of human–environment systems, coupled SESs, and interregional linkages, attribute datasets should be transformed into various relational datasets. In addition to the administrative division, the physical geographical unit (e.g., watershed and lake basin) should be emphatically considered in data fusion and database building. With regard to the innovation of analytical methodologies, future research should explore the transdisciplinary application of methods derived from economics (e.g., composite indexes and econometric models), sociology (e.g., social network and structured interview), geography (e.g., spatial analysis and geographical statistics), ecology (e.g., field observations and laboratory experiments), management, etc.

5. Conclusions and Discussion

Integrating the effects of key processes across the full range of scales from local to global is crucial for understanding the interactions between the human sphere (or social systems) and the natural sphere (or ecological systems) [16,23,121]. Such an understanding calls for long-term integrated research on the sustainability of SESs and relevant issues in key places and regions of the world. Previous literature has also indicated that, in addition to global-scale analyses, SDG achievement and interactions at the subnational (or regional) scale deserve more attention from policymakers and scholars [2,8,25]. Therefore, it is essential and urgent to conduct systematic and in-depth research into the sustainable development of regions with different territorial functions, especially those highly urbanized regions with complex human–environment relations, around the world.

Located in the eastern coast of China, the YRD is known as one of the emerging global city-regions, as well as one of the urban agglomerations or integrated regions with the highest level of urbanization, economic growth, and social welfare in China and the Global South. The YRD and its major cities, industrial clusters, and lead firms play an increasingly vital role in the globalized economy and Chinese path to modernization. Meanwhile, the eco-environmental systems of the YRD are vulnerable to and have been largely influenced by the rapid and continuous changes in socioeconomic systems, such as the irrational and extensive utilization of natural resources. The development mode and predicaments, especially the increasingly striking contradiction within the human–environment system of the YRD, are representative of mega-city-regions located in emerging economies. The YRD could be taken as an experimental site for the integrated research on geographical science, sustainability science, and human–environment systems [131,132]. To better understand and promote high-quality-oriented, integrative, and sustainable development of the YRD, this paper aims to propose a conceptual framework to link regional integration with sustainable development at the subnational scale, and then generate future research agendas related to the YRD based on research gaps and the Chinese contexts.

We mainly reviewed the literature on the YRD from perspectives such as geography, human–environment interaction, and integrated and sustainable development. With particular attention given to issues including urbanization, economic restructuring, natural resource utilization, eco-environmental changes, and collaborative governance, the existing studies and relevant findings have largely advanced our understanding of the temporal and spatial variations of socioeconomic and eco-environmental systems in the YRD. The literature also indicates an increasing interest in the interactions between social and ecological systems. However, previous studies on the human–environment system or SESs of the YRD seem to be slightly fragmented. Theoretical research on regional integration and empirical research on SDG achievements and interactions in the YRD are also thin on the ground, which is inconsistent with the intellectual support needed for regional integrated and sustainable development.

This paper tries to develop a conceptual framework to make the causal association between integration and sustainable development at the subnational scale (or in a trans-administrative mega-city-region). We argue that regional sustainable development practices and SDG implementation and realization could be placed in the process of regional integration. By highlighting the shared visions, multi-dimensional synergies, interregional cooperation, stakeholders' joint-action, institutional reformation, and mission-oriented and place-based policies, the process of regional integrative development could be an effective strategy or approach to achieve sustainable development at the subnational scale. To better understand and unravel complex nexuses between regional integration and regional sustainable development, future research should pay more attention to the interdisciplinary, transregional, and multi-scale attributes of issues related to the interactions between the human sphere and the natural sphere in the YRD. We propose the following six research agendas: First, linking the SDGs to regional integrated development in the YRD, the assessment of SDG achievement, and the interactions between the 17 SDGs call for more scholarly investigation. Second, based on the analyses of single socioeconomic and eco-environmental phenomena (or factors), the evolutionary dynamics, feedback mechanisms, and regime shifts of SESs in the YRD need long-term systematic research. Third, more research attention should be paid to the driving mechanisms, achievement approaches, and evaluative criteria of regional integration in the YRD and other integrative regions at the subnational scale. Fourth, more detailed research on the interactions of geographical scales, particularly the role and position of the YRD within the global or Chinese context, is also needed in the future. Fifth, studies based on perspectives such as smart specialization should be conducted to discuss governance structures, institutional settings, and policy instruments related to interregional cooperation and synergetic growth in the YRD. Sixth, the application of multi-source datasets and the integration of interdisciplinary methodologies should be strengthened in future research.

The special issue "Regional Sustainable Development of Yangtze River Delta, China" and this paper aim to call for more scholarly attention on noteworthy topics related to regional integrated and sustainable development in the YRD on the one hand, and provide alternative perspectives and applicatory approaches for the analysis of the sustainability of SESs and the achievement of SDGs at the subnational scale (or within regions with unique territorial function) on the other hand. Research articles included in this special issue examine a wide range of agendas, such as industrial restructuring, technical progress, population migration, urban systems, urban–rural relations, land use change, ecological systems, environmental protection, and collaborative governance, related to the YRD. Some scholars further investigated the interactive dynamics between urbanization (or land use change) and ecosystems (e.g., ecological services) [133–136]. These studies and relevant findings will advance our understanding of regional integration and sustainable development practices in the YRD. However, theoretical discussion and empirical research on the dynamics of regional integration and the sustainability of regional SESs, as well as SDG achievements and interactions in the YRD are quite limited in this special issue. It is difficult for this paper or special issue to cover all seminal works, enlightening findings, and prospective research agendas. We hope this paper or special issue becomes an initial motion to expand and enrich relevant research.

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Quantitative Evaluation of Ecological Stress Caused by Land Use Transitions Considering the Location of Incremental Construction Lands: The Case of Southern Jiangsu in Yangtze River Delta Region

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Abstract: With their significance in connecting socio-economic development and related eco-environmental consequences, land use transitions have gradually become the focus of land change science and sustainability science. Although various research studies have determined the ecological effects of land use transitions and provided suggestions to regulate them, few studies have investigated the different ecological stress of construction lands from the perspective of their spatial locations in ecologically differentiated regions. Taking economically developed and highly urbanized southern Jiangsu in Eastern China as an example, we developed a process-based method to indicate the spatial heterogeneity of ecological suitability and divided southern Jiangsu into five-level ecological zones accordingly. Considering that construction lands in ecological zones with higher ecological suitability levels cause greater ecological stress, we evaluated the ecological stress levels of incremental construction lands at different stages after 1990. Then, we carried out the calculation of county-level ecological stress and county-level zoning based on both the area and ecological stress level of their incremental construction lands. Results indicated that ecological zones with the highest to lowest ecological suitability levels accounted for 49.85%, 25.73%, 15.56%, 6.51%, and 2.34%, respectively. The majority of the incremental construction lands had the highest and moderately high ecological stress levels, and they were mainly distributed in areas along the Yangtze River and around Taihu Lake. The general ecological stress level of southern Jiangsu was at a relatively high level at each stage, but the county-level patterns of ecological stress levels were spatially different. As determined from the relationship between the amount of incremental construction lands and the average stress level associated with these lands in each unit, four types of zones, i.e., H-H, H-L, L-H and L-L zones, were identified, and targeted suggestions on land use regulations were proposed. We conclude that the spatial distribution of incremental construction lands significantly affects their ecological consequences from the perspective of maintaining ecosystem integrity. Both construction lands and ecological suitability are location specific, so the location-oriented evaluations could provide an effective approach for determining the spatial patterns of land use transitions based on spatially differentiated ecological consequences. It is essential to propose location-specific policies to carry out spatially precise ecological restoration and the redistribution of incremental construction lands.

Keywords: land use transitions; ecological stress; ecological process; construction lands; location; southern Jiangsu; China

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1. Introduction

Since the late 1970s, unprecedented urbanization and industrialization have taken place in China [1,2]. According to the China Statistical Year Book in 1987 and 2016, the scale of construction land in China was reported to be 386,000 square kilometers in 2015, accounting for 4.1% of the total land area, and this area has expanded by 190% since 1986. The rapid expansion of construction lands has not only resulted in various issues, such as social conflicts and economic polarization [3–5] but has also imposed serious challenges associated with food deficits and ecological security [6–8]. Moreover, land use transitions have taken place recently and have become the focus of land use research, especially in rapid developed and urbanized China [9–11]. The ecological effects of recent land use transitions are more diverse and complicated than traditional land use changes [12,13]. Aiming to promote sustainable development and coordinate land development and ecological protection, the current state of research suggests that assessing the spatial stress associated with land use transitions and the expansion of construction lands is urgent for providing insight into policymaking and for regulating land use transitions [14,15].

Existing published research has focused on ecological stress assessments of the expansion of construction lands from various perspectives and at different levels. In early studies, many different indicators and metrics were designed to analyze the state of or spatial and temporal changes in regional ecosystems, including the areas and types of construction lands, ecosystem services, ecological vulnerability and various landscape-level metrics [16–18]. These methods are still widely used with the help of multi-source land use, land cover or ecological/environmental data. The abovementioned studies effectively indicated the ecological consequences of land use transitions from certain perspectives, but the cause of the above ecological consequences i.e., land use transitions, have not been given sufficient attention [19]. For land use transitions, it is widely accepted that the land use morphology includes dominant morphology and recessive morphology [20,21]. The spatial pattern of land use types, especially the location of construction lands, is among the most significant topics of land use transition research [9,19]. However, some direct indicators reflecting the state or change process of land use have been proposed recently, such as the amount and proportion of construction lands [19,22]. Some complicated metrics have been proposed by adopting the amount or proportion of land use as an output-oriented or input-oriented parameter [23,24]. However, the location of construction lands was rarely considered [25,26].

Ecosystems are characterized by integrative and mutually relevant components, so the protection of a specific ecological process is critical for improving the efficiency of ecological protection [27–29]. However, the ecological suitability is spatially differentiated, and different locations in certain ecosystem are of unlikely significance in maintaining ecosystem health [30,31]. Moreover, according to the landscape ecology theory, maintaining ecological processes by creating continuous ecological corridors is of equal or even higher importance than restoring some landscape patches [32,33]. Landscape structures, patterns, and processes are highly interrelated and interactive, and protected ecological processes promote landscape connectivity and avoid fragmentation among isolated patches [34,35] Therefore, the spatial differentiation of ecological suitability should be considered in evaluating the ecological consequences of construction lands [19].

On the other hand, the land suitability for development is influential for the spatial expansion of construction lands, and lands with high development suitability are usually the optimal area for land development and the allocation of construction lands [36,37]. Construction lands might be location at zones with high development suitability before the 21st century, while the ecological suitability of those zones is neglected sometimes, causing obvious ecological stress accordingly [38,39]. The location of construction lands should be emphasized, as the chosen locations are critically significant in maintaining regional ecological safety by safeguarding and controlling ecological processes [25,40]. Although some researchers have carried out studies to indicate the effect of location on the ecological stress associated with construction lands, in these studies, only the effects of construction lands at certain stages were analyzed [19,26]. The expansion of construction lands reflects the spatiotemporal patterns of land use transitions, and targeted studies are still needed to better indicate the different ecological stress levels caused by the spatially differentiated expansion of construction lands.

The ecological stress effect caused by the locations of construction lands is influenced by the spatial heterogeneity of regional ecosystems, and it is widely accepted that construction lands in regions with higher ecological suitability levels cause higher ecological stress to regional ecological safety [26,35]. Accordingly, it is of primary importance to evaluate the spatial heterogeneity of ecological suitability [41,42]. Early studies were mostly conducted with the help of single-element or multifactor assessment approaches, and the importance of ecological processes was not significantly emphasized [25,43]. To reveal the role of these ecological processes, conservation biologists have developed various methods, including biotelemetry, tagged release capture, mass tagged capture, and species surveys, to track the movement of specific species and determine the dispersal processes that promote species migration [44,45]. However, the methods listed above are often difficult and costly at the regional scale, and high-efficiency model simulations with low data requirements have been widely adopted, such as cellular automata (*CA*) models, system dynamics (*SD*) models, and other spatially explicit models, (see, for example, [46–49]). Among these models, the minimum cumulative resistance (*MCR*) model is one of the most widely used simulation models. This model has its roots in the recognition of dispersal processes or "stepping stones" and was recently widely used in ecological process simulations and ecological network constructions [50–52]. Accordingly, spatial differences in ecological suitability have been effectively identified from the perspective of maintaining necessary ecological processes [19,43,53].

Overall, the ecological stress caused by construction lands differs spatially, and these differences are caused by the spatial locations of construction lands and the location-related differentiation of ecological suitability. The spatial conflict between ecological protection and expansion of construction lands existed and brought challenges to regional sustainable development. However, the spatial differentiation of ecological suitability and related ecological stress of construction lands during different stages of land use transitions have not been analyzed. To better solve the above-mentioned issues and promote regional sustainable development by optimizing the spatial pattern of land development, it is urgent to consider ecological process analyses to indicate ecosystem heterogeneity and to consider the location effect of construction lands to assess the associated ecological stress level [54,55].

We chose economically developed and rapidly urbanized southern Jiangsu in Eastern China as an example and tried to answer the following questions: (1) How do we indicate the spatial differentiation of ecological suitability, especially from the perspective of maintaining necessary ecological process? (2) What are the spatial patterns of the expansion of construction lands and how can we evaluate their ecological stress caused by different locations during transitional stages? (3) What are the spatial patterns and temporal changes of differential ecological stress of construction lands? In the following parts, we firstly provide a brief introduction of southern Jiangsu and the adopted methodology, examine the spatial ecological suitability pattern based on the significance of maintaining ecological processes, and then evaluate the differentiated ecological stress levels caused by the presence of incremental construction lands at different stages. Finally, we discuss our potential contributions and policy implications from the perspectives of promoting ecological processes and optimizing the spatial distribution of construction lands.

2. Methodology

2.1. Study Area

Southern Jiangsu is located in the Yangtze River Delta region (YRD) of Eastern China covers a land area of 28,000 km^2. There are five prefectural cities in southern Jiangsu (i.e., Nanjing, Wuxi, Changzhou, Suzhou, and Zhenjiang), and these cities are further divided into 33 county-level units (Figure 1a). It is one of the most developed regions in China [2]. In 2015, it had 33.24 million residents and a regional gross domestic product (GDP) of RMB 4151.87 billion, which were about 1.58 and 14.33 times those in 1990. As population and industries have grown rapidly in this region, construction lands have expanded dramatically (Figure 1b). After 1990, the expansion of construction lands was about 4818 km^2, and the total area of construction lands reached 6617 km^2 by 2015, accounting for 23.45% of the total regional land area [26]. The urbanization process of southern Jiangsu has experienced several transitional stages influenced by the interactions of industrialization, urbanization, globalization and marketization [40,56]. Land use transitions occurred accordingly, which are represented by the changing spatial and temporal expanding patterns of the construction lands at different stages [57,58]. However, the ecological effects and their differences of construction lands that occur during several different transitional stages are rarely researched, especially from the perspective of differentiated spatial location of construction lands [19]. As the rapid expansion of construction lands has occupied a large amount of ecologically suitable lands and brought obvious ecological destruction and environmental degradation, it is necessary to conduct detailed research and provide insight into the spatial and temporal ecological stress patterns caused by the expansion of construction lands.

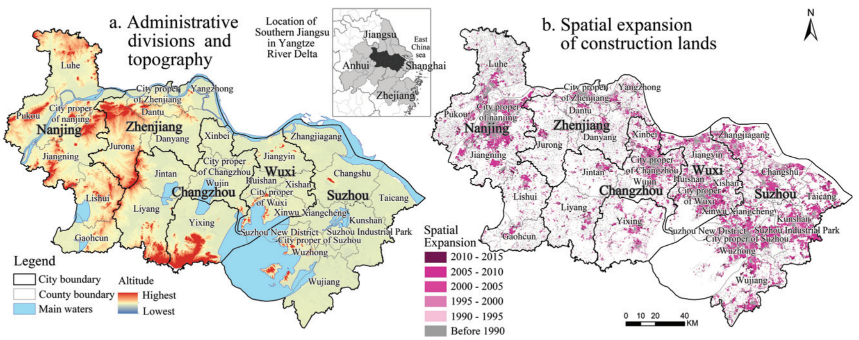

Figure 1. Administrative divisions, topography and expansion of construction lands in southern Jiangsu.

2.2. Methodologies and Data

2.2.1. Model Description for Ecological Process Simulations

As discussed above, the ecological effects of construction lands are location specific, and more ecologically suitable regions experience higher ecological stress levels when land development occurs there [19]. Moreover, the spatial differentiation of ecological suitability is affected by the importance of maintaining ecological processes. Besides the process of species dispersal, the expansion of ecological spaces is also a typical ecological process, and its simulation is feasible with some originally species-specific methods, including the *MCR* model [48,53]. As the *MCR* values of the above model indicate the cumulative resistance to the expansion of ecological spaces, zones with lower *MCR* values are more suitable as potential ecological spaces [51,59]. Therefore, we first identified ecological suitability through ecological process simulations with the *MCR* model. According to the studies of Knaapen et al. [60], Yu [61] and Li et al. [59], the *MCR* model can be expressed as follows:

$$MCR = f_{\min} \sum\nolimits_{j=n}^{i=m} D_{ij} \times R_i \quad (1)$$

where f is a monotonically increasing function that indicates the least resistant relation between unit i and source unit j under the restriction of a certain resistance surface, min denotes the minimum cumulative resistance value produced in different processes from unit i to unit j, D_{ij} is the spatial distance between i and j, and R_i represents the resistance of cell i on the route from unit i to j. The *MCR* value reflects the minimum cumulative resistance and maximum migration accessibility or ecological spatial expansion ability of species from the source to the target.

Based on the *MCR* analysis, the most accessible paths (i.e., potential ecological processes) between ecological sources and target patches can be identified. The *MCR* values of different patches denote their resistance to or suitability for the migration of species or the expansion of ecological spaces. Patches with higher *MCR* values are less suitable for ecological expansion and are accordingly defined as having lower ecological suitability levels [61].

2.2.2. Model Variables

All the aforementioned analyses were conducted with the help of a cost–distance module in Esri's geographical information system ArcGIS after two essential variables were obtained. The "source" includes the input variables *i* and *j* in Equation (1) and refers to landscape patches that have suitable habitats and provide indispensable ecosystem services; these patches could also be targets in the *MCR* analysis [48,61]. Based on existing research and public documents, the important and ecological protection lands in a major function-oriented zoning (*MFOZ*) region are considered naturally protected regions with significant natural/cultural values and biodiversity [62]. Therefore, we chose the ecological protection lands among the published MFOZ information of Jiangsu as the source; these areas included nature reserves, forest parks, scenic spots, geo-parks, drinking water protection areas (*DWPAs*), flood storage and detention basins (*FSDBs*), fisheries and aquatic resource protection areas (*FARPAs*), and important wetlands, water-dilution channels, ecological forests, and water conservation and reserve areas (*WCRPAs*) (Figure 2a). The cumulative area of these regions is approximately 7055 km^2, accounting for 25% of southern Jiangsu.

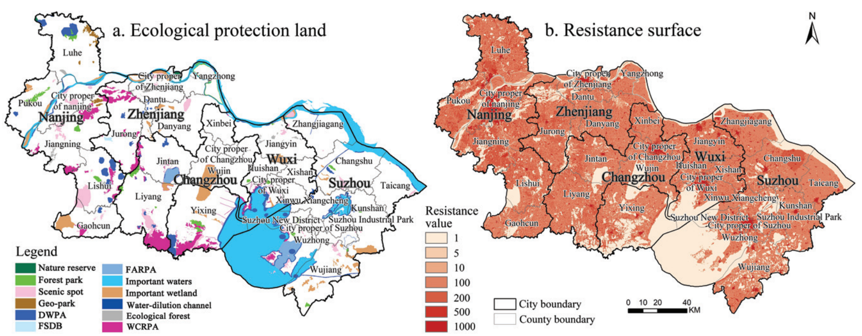

Figure 2. Ecological protection lands and resistance surface of southern Jiangsu.

The other necessary variable, i.e., the resistance surface, is designed based on the resistance values of different land use types; these values are relative and have different extents [51,63]. Basically, land use types with higher human disturbance levels, such as greater economies and population agglomeration degrees, usually have greater resistance to the dispersal of common species [48,59]. Li et al. [59] and Liu et al. [53] used the values 1–5 to indicate differences in resistance values, while Su et al. empirically assigned the resistances of different land use types, i.e., 0 for woodlands, 10 for water bodies and shrublands, 30 for gardens and grasslands, 100 for paddy fields, 300 for dried fields, 400 for construction lands and 500 for highways [52]. Adriaensen et al. pointed out that larger relative differences among various land use types are more effective in deviating further from the default straight line between the source and target patches [48]. Based on existing studies and aiming to magnify the different ecological disturbance levels of land use types, we herein assigned resistance values to different land use types, i.e., 1000 for urban lands, 500 for rural settlements and independent industrial and mining land (IIMLs), 200 for dry croplands, 100 for paddy lands and unused lands, 50 for low-coverage grasslands, 30 for moderate-coverage grasslands, 10 for high-coverage grasslands, sparsely forested lands, and other forestlands, 5 for shrublands, and 1 for woodlands and water bodies. Based on land use data collected in 1990, the resistance surface was obtained (Figure 2b).

2.2.3. Recognition of Construction Lands with Different Ecological Stress Levels

Based on the *MCR* analysis results, regions with lower *MCR* values are widely accepted to be more suitable for the expansion of ecological spaces and hence, have higher ecological suitability levels [26,53]. To quantitatively evaluate the ecological stress levels of construction lands, it is essential to define the levels of ecological suitability. There were no widely accepted quantitative criteria for determining it. Although more levels could indicate the spatial differentiation of ecological suitability more precisely, it would bring higher complexity accordingly. The recognition of five level suitability was widely accepted, as it is both robust in indicating spatial differentiation and feasible in quantitative calculation [19,53]. Moreover, it was enough to reflect the differences of the ecological stress of construction lands. Therefore, we chose to identify five ecological zones with different ecological suitability levels, i.e., we differentiated zones with highest, moderate-high, moderate, moderate-low, and lowest levels. The zone with the highest *MCR* value had the lowest ecological suitability, as greater disturbances were caused to ecological processes in this region, and vice versa. Reclassification by the natural breaks (Jenks) method was adopted to divide the whole region into subregions with different ecological suitability levels, as this method could minimize differences within groups and maximize differences among groups.

As mentioned above, the ecological stress associated with construction lands is affected by the spatial distribution of the construction lands and the spatial heterogeneity of the ecological suitability level. Basically, construction lands distributed in ecological zones with higher ecological suitability levels cause greater ecological stress. To quantitatively calculate their ecological stress levels, the construction lands in the five designated ecological zones were assigned corresponding stress values, i.e., 5, 4, 3, 2 and 1 for lands in ecological zones with the highest, moderate-high, moderate, moderate-low, and lowest ecological suitability levels.

In this part, maps of both *MCR* values and zones with different ecological suitability levels were obtained. The assigned ecological stress induced by the presence of construction lands at different stages was also identified.

2.2.4. Calculation of County-Level Ecological Stress

As administrative districts, especially counties, are the basic units applied for land use regulation and the implementation of related policies, we calculated the general ecological stress levels corresponding to different units. The above analysis allowed the ecological stress associated with construction lands and the amount of construction lands corresponding to each unit in the five established ecological zones (i.e., zones with different ecological stress levels) to be recognized with the help of ArcGIS software. For each unit, as the amounts or proportions of construction lands with different ecological stress levels are quite diverse, their general ecological stress level also differs. The general stress value can be calculated with the following equation:

$$ES_i = \frac{\sum_{j=1}^{m} A_{ij} \times s_j}{\sum_{j=1}^{m} A_{ij}} \quad (2)$$

where ES_i is the general ecological stress of unit *i* induced by the presence of construction lands; A_{kj} is the area of construction lands associated with ecological stress value *j*; S_j is the ecological stress value of the abovementioned construction lands; and *j* is the stress level, which varies from 1 to *m*, and *m* = 5, as five levels are identified in this research. Similarly, the general ecological stress value of southern Jiangsu was also obtained.

As all construction lands were assigned ecological stress values from 1 to 5, the general stress values of the 33 units and the whole of the southern Jiangsu region theoretically ranges from 1 to 5. However, as construction lands are spatially concentrated in reality, the general stress value might also have a specific extent. In this research, the obtained general ecological stress ranged from 1.99 to 4.92, except in the city proper of Suzhou between

2010 and 2015, when there were no incremental construction lands present. We designed a unified classification standard to indicate the spatial differentiation of the county-level ecological stress according to the results calculated for the 33 units at different stages (from 1.88 to 4.92), i.e., <2.00, 2.00–2.75, 2.75–3.50, 3.50–4.25, and 4.25–5.00.

2.2.5. County-Level Zoning Based on Both the Area and Ecological Stress Level of Incremental Construction Lands

Both the amount of and ecological stress associated with incremental construction lands are influential for the future land use regulation of a certain unit. Therefore, we carried out county-level zoning after comparing these metrics in a given unit to the regional average. To simplify this process and compare the results, the whole stage from 1990 to 2015 was chosen as the target phase. With 33 units as the input, the average area of incremental construction lands and ecological stress level of southern Jiangsu were 146.04 km^2 and 3.81, respectively. Therefore, units with both greater construction land areas and higher stress levels were defined as H-H zones. Similarly, H-L, L-H, and L-L zones were also identified.

2.2.6. Data Source and Processing

In this research, we aimed to quantitatively evaluate the ecological stress associated with construction lands and indicate the process and spatial pattern of land use transitions; to this end, land use data representing 1990, 1995, 2000, 2005, 2010 and 2015 were adopted. These data were provided by the Data Center for Resources and Environmental Sciences (RESDC) at the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 22 May 2021) and were interpreted based on Landsat-Thematic Mapper (TM) images at high precision. With land use data from 1990 to 2015, the expansion and spatial distribution of incremental construction lands were obtained in five stages, i.e., 1990–1995, 1995–2000, 2000–2005, 2005–2010 and 2010–2015. Additionally, administrative division data were also provided by RESDC. The sources input into the *MCR* model, i.e., the ecological protection lands, were obtained from published MFOZ data representing Jiangsu.

3. Results

3.1. Spatial Distribution of Zones with Different Ecological Suitability Levels

The spatial distribution of *MCR* values was similar to the irregular spread of contour lines. Basically, regions close to cities had higher MRCs, as more construction lands were distributed in these regions, while water bodies and mountains/hills had lower *MCR* values (Figure 3a). After reclassification, the five ecological zones with different *MCR* values and ecological suitability levels accounted for 49.85%, 25.73%, 15.56%, 6.51%, and 2.34% of the zones with the highest to lowest ecological suitability levels, respectively. The most suitable zones (with the highest ecological suitability levels and lowest *MCR* values) were mainly concentrated in areas surrounding Taihu Lake and the Yangtze River as well as in the Yixing-Liyang and Mao mountainous regions, which are closer to ecological lands and have low anthropogenic disturbance levels (Figure 3b). The ecological zones with the lowest suitability levels were concentrated in urbanized areas, including in the cities of Nanjing, Suzhou, Wuxi, and Changzhou and in eastern regions close to the Shanghai metropolitan area (Figure 3b). These regions are characterized by widely distributed construction lands, dense populations and industrial agglomerations.

3.2. Spatial Distribution of Incremental Construction Lands

After 1990, construction lands in southern Jiangsu expanded drastically, but showed an obvious difference among different growth stages. The expansion of construction lands was 974.65, 456.49, 767.18, 2123.28 and 496.55 at stages from 1990 to 1995, from 1995 to 2000, from 2000 to 2005, from 2005 to 2010, and from 2010 to 2015, respectively. The period from 2005 to 2010 had the fastest growth, when the boost of export-oriented economy caused rapid industrial development and the inflow of floating population as China entered WTO. Hereafter, the expansion decreased obviously as some restrictive policies on land development were proposed under the background of high land use intensity. Basically, the expansion of construction lands at early stages was basically promoted by the socioeconomic development, while the slowdown in recent years was led by the restriction of land development and the protection of ecological lands and crop lands.

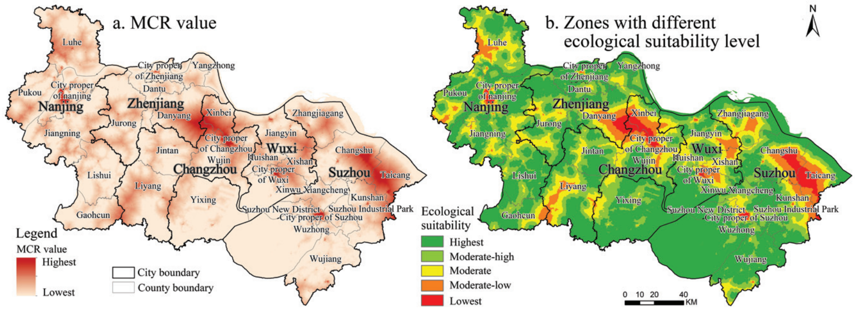

Figure 3. *MCR* values and zones with different ecological suitability levels in southern Jiangsu.

Among the five prefectural cites, Suzhou experienced the fastest construction land growth, reaching 1892 km^2. It accounted for 39.29% of the total increment in southern Jiangsu. This is basically consistent with its proportion of economy and population, i.e., 40.58% and 35.22%, respectively. Suzhou is closest to Shanghai in southern Jiangsu and is also among the most developed cities in China, causing greater demand for construction lands. In terms of county-level units, the cities and surrounding units of Nanjing, Suzhou, Wuxi and Changzhou, as well as Jiangyin, Zhangjiagang, Taicang and Kunshan along the Yangtze River, had greater expansion than other units (Figure 4). The expansion of Kunshan was the largest, at approximately 13 times that of the city proper of Wuxi, the unit with the lowest expansion. The expansion of the cities of Jiangning in Nanjing, Changshu, Wujiang and Zhangjiagang in Suzhou, Jiangyin and Yixing in Wuxi and Wujin in Changzhou were also great, with expansion amounts over 200 km^2. In contrast, the expansion of Gaochun in Nanjing and the cities of Suzhou and Wuxi were smaller, with expansion amounts less than 50 km^2. In general, the units around Taihu Lake and along the Yangtze River dominated the expansion of construction lands in southern Jiangsu after 1990. This is also consistent with the pattern of population agglomeration and industrial development.

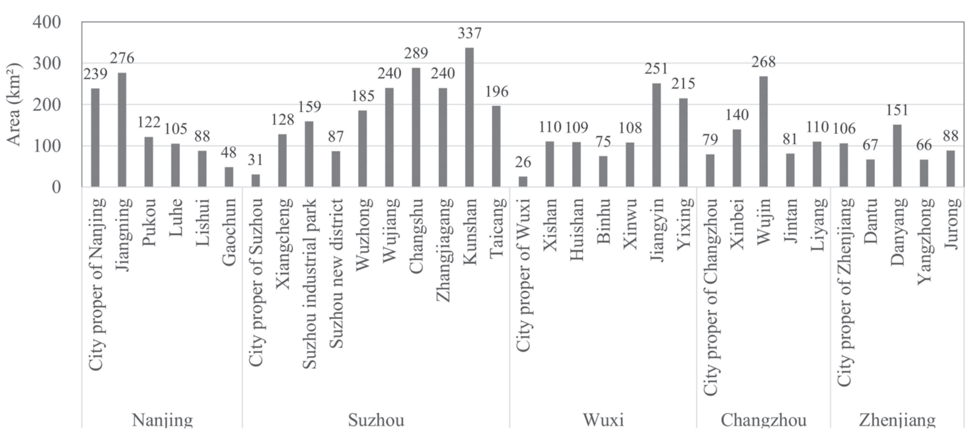

Figure 4. The expansion of construction lands in different units from 1990 to 2015.

3.3. Spatial Differentiation of Incremental Construction Lands with Different Ecological Stress Levels

In total, our overlay analysis of ecological zones and construction lands indicated that the construction lands with the lowest, moderate-low, moderate, moderate-high, and highest (from level 1 to 5) ecological stress values (i.e., those distributed in ecological zones with ecological suitability levels of 1 to 5) were 153.52, 433.51, 1007.22, 1792.62, and 1431.29 km^2, respectively. The majority of these areas had highest and moderate-high ecological stress levels, while areas with the lowest ecological stress made up the smallest fraction.

The ecological stress associated with incremental construction lands showed similar patterns in each stage (Figure 5). There were more lands with highest or moderate-high stress levels than the other categories, while lands with the lowest stress levels made up the smallest fraction. However, there were still slight differences among different stages. From 1990 to 1995, the area of construction lands with moderate-high stress levels was greater than the areas of construction lands with highest and moderate stress levels, but construction lands with the highest stress levels were slightly larger than those with moderate-high stress levels from 1995 to 2000. From 2000 to 2005 and from 2005 to 2010, the area of lands with moderate-high stress levels again became dominant. From 2010 to 2015, the largest fraction was again replaced by lands with the highest stress level. In general, construction lands with highest and high stress levels alternately dominated the incremental construction lands, indicating that the ecological stress caused by incremental construction lands remained at a high level in each stage.

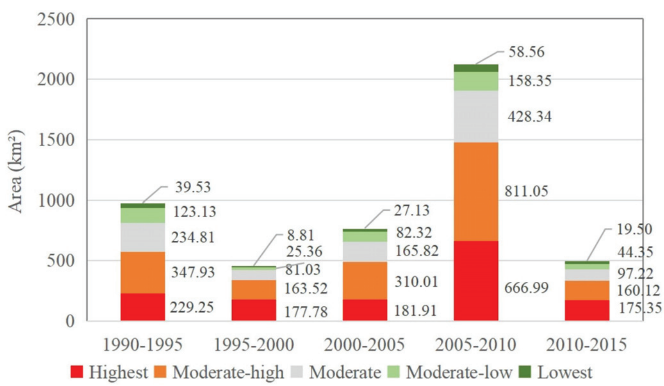

Figure 5. Areas of incremental construction lands associated with different ecological stress levels.

Spatially, the construction lands with the highest ecological stress levels were mainly distributed in areas along the Yangtze River and around Taihu Lake (Figure 6a). Wujiang, Wuzhong and Binhu around Taihu Lake and Jiangyin, Zhangjiagang, and the cities of Zhenjiang and Nanjing along the Yangtze River had more lands with the highest stress levels. Moreover, some county-level units with high proportions of waters, hills or mountains also had large land areas with the highest stress levels, including Suzhou Industrial Park, Lishui, Kunshan, Pukou, Jiangning and Yixing. In contrast, the lowest-stress construction lands were mainly distributed in the surrounding units of cities, such as around the city proper of Changzhou and the adjacent Xinbei, the city proper of Wuxi and the adjacent Xishan, Xinwu, and Taicang, and Changshu and Kunshan in the eastern part of southern Jiangsu. There were fewer ecological lands and with lower ecological suitability, and the lower ecological stress was caused by construction lands.

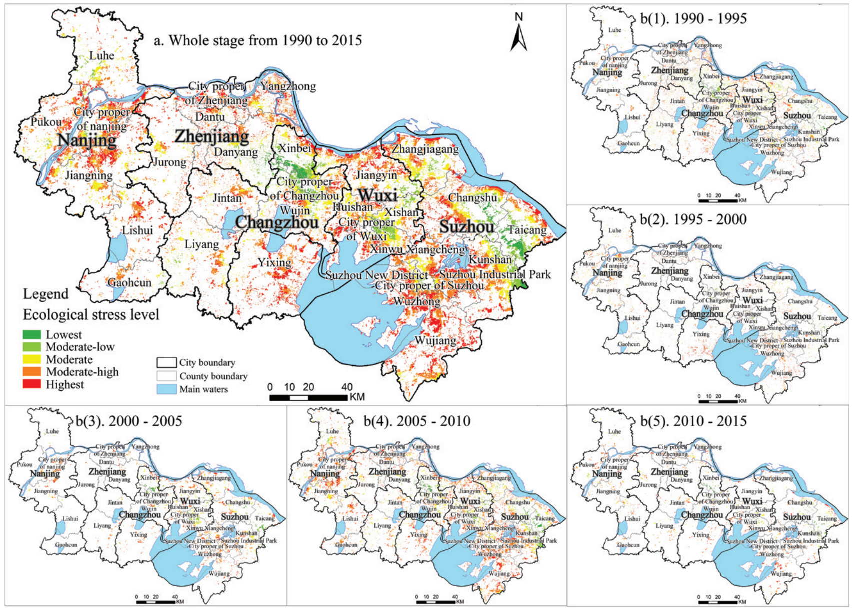

Figure 6. Spatial distribution of construction lands associated with different ecological stress levels in each stage.

The spatial differentiation of construction lands associated with different ecological stress levels showed similar patterns in each stage (Figure 6b). Areas associated with high ecological stress levels were mainly concentrated at the units along the Yangtze River, around Taihu Lake and in mountainous areas, while construction lands associated with relatively low stress levels were basically distributed at cities or in some counties with low ecological suitability levels, including in southern Taicang, eastern Changshu and northwestern Kunshan.

3.4. Patterns of Units with Different Ecological Stress Levels

From 1990 to 2015, the general ecological stress level associated with incremental construction lands was 3.81, characterizing a relatively high level. This is because the majority of construction lands were of highest and moderately high ecological stress levels. As this value is affected by the spatial differentiation of incremental construction lands associated with different ecological stress levels, the average ecological stress level associated with each unit differed significantly (Figure 7a). Among the units, the ecological stress of the city proper of Changzhou was low (i.e., 2.38), while that of Binhu of Wuxi was highest (i.e., 4.67) and was approximately 1.96 times that of the city proper of Changzhou. Based on the reclassification results, eight units had ecological stress levels higher than 4.25, and these units were mainly distributed around Taihu Lake and along the Yangtze River, including Binhu and Yixing of Wuxi, Wuzhong and Wujiang of Suzhou, Dantu, Yangzhong and the city proper of Zhenjiang, and Lishui of Nanjing. Conversely, there were no units with stress levels lower than 2.00. The stress levels of 3 units were between 2.00 and 2.75, and these units were mainly distributed along the Yangtze River, including Taicang of Suzhou, Xinbei, and the city proper of Changzhou. Units with stress levels between 3.50 and 4.25 dominated the whole region, and the total number of units falling within this range was 17, further indicating that the ecological stress associated with incremental construction lands was at a relatively high level.

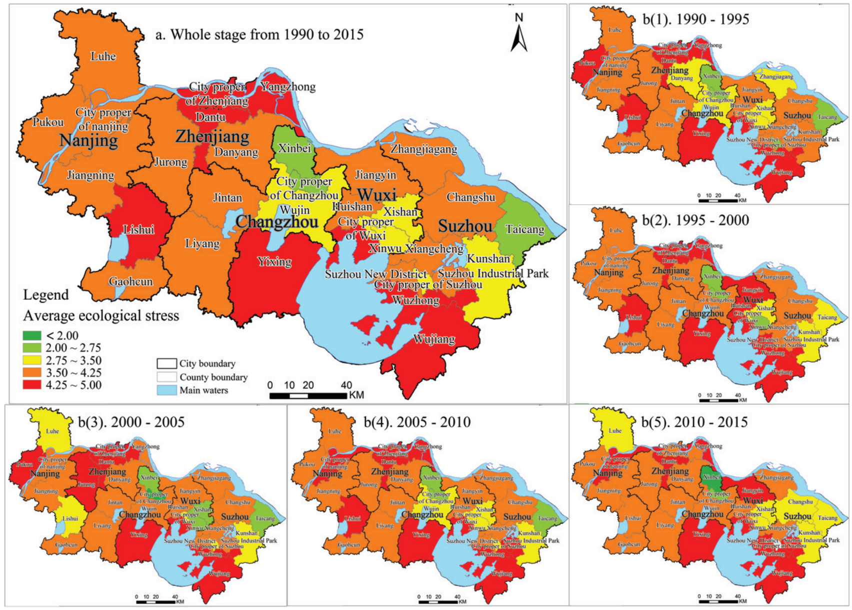

Figure 7. Spatial distributions of units with different ecological stress levels in each stage.

Since 1990, the general ecological stress levels determined at each stage were 3.62, 4.04, 3.70, 3.88 and 3.86, showing a fluctuation trend of "increasing-decreasing-increasing". The spatial pattern of each stage showed similar characteristics to that of the whole stage, i.e., units with moderate-high stress levels dominated southern Jiangsu, followed by those with the highest and moderate-low stress levels (Table 1; Figure 7b). Moreover, few units had ecological stress levels below 2.00, including the city proper of Changzhou from 2000 to 2005 and Xinbei in Changzhou from 2010 to 2015. Specifically, as the construction lands in the city proper of Suzhou remained stable from 2010 to 2015, the ecological stress level of this unit was 0.

Table 1. Numbers of units with different ecological stress levels in each stage.

Stage	Lowest <2.00	Moderate-Low 2.00~2.75	Moderate 2.75~3.50	Moderate-High 3.50~4.25	Highest 4.25~5.00
1990–1995	0	4	6	14	9
1995–2000	0	3	4	15	11
2000–2005	1	4	5	15	8
2005–2010	0	3	6	14	10
2010–2015	2	1	6	14	10
Total	0	3	6	16	8

3.5. Zones with Different Amounts of and Ecological Stress Levels Associated with Incremental Construction Lands

As determined from the relationship between the amount of incremental construction lands and the average stress level associated with these lands in each unit, Moran's I value obtained from the local indicators of spatial association (LISA) analysis was −0.1531, indicating that units with greater expansion areas had lower average stress values at the county scale. The more construction lands expanded from 1990 to 2015 in a unit, the lower the ecological stress level of that unit. According to the relationship between the expansion amount of each unit and its average ecological stress level, four types of zones were identified further (Figure 8).

Figure 8. Zones with different construction land expansion extents and their corresponding ecological stress levels.

(1) H-H zones. These zones included units with both greater construction land expansion amounts and higher ecological stress levels than the corresponding regional averages, comprising Jiangning of Nanjing, Jiangyin and Yixing of Wuxi, and Suzhou Industrial Park, Wuzhong and Wujiang of Suzhou. These units were rapidly developing areas with significant populations and industry agglomerations after 1990, causing the remarkable expansion of construction lands. As they were also zones with higher ecological suitability, the ecological stress caused by construction lands was at a high level. Taking the city proper of Nanjing as an example, from 1990 to 2015, its population increased from 2.32 million to 5.26 million, and its GDP increased from RMB 12.34 billion to 444.58 billion. However, as water bodies and mountains are also widely distributed in this unit, they contributed a higher ecological suitability level. Therefore, the rapid expansion of construction lands brought more serious disturbances to ecological safety, and a higher ecological stress level was caused accordingly.

(2) H-L zones. These zones comprised units with both less construction land expansion and lower ecological stress levels than the corresponding regional averages, including Danyang of Zhenjiang, Wujin of Changzhou, and Kunshan, Taicang, Changshu and Zhangjiagang of Suzhou. These units contain developed areas with rapidly growing populations and industry agglomeration after 1990, causing significant construction land expansion. Kunshan was a typical case; in this city, the population increased from 0.56 million to 1.65 million and the GDP increased from RMB 1.86 billion to 308.00 billion. As the above regions were also less ecologically suitable, the growth of a large amount of construction lands did not cause high ecological stress levels.

(3) L-H zones. These zones included units with less of construction land expansion but higher ecological stress levels than the regional averages. There were 13 units in this category in total, accounting for 40% of all units, mainly including units surrounding cities or in ecologically suitable regions. Although the expansion construction lands were relatively small in these units, the ecological stress levels were higher than the regional average. The construction lands of the city proper of Zhenjiang increased by approximately 106 km^2, as its proportion of construction lands was high before 1990 and expansion of construction lands was restricted accordingly. However, as this city is located along the Yangtze River with a high ecological suitability level, its ecological stress level was 4.41, much higher than the regional average (i.e., 3.81).

(4) L-L zones. This category included units with both less construction land expansion and lower ecological stress levels than the corresponding regional averages and comprised Luhe of Nanjing, the city proper of Xinbei of Changzhou, the city proper of Suzhou, and the cities of Xinwu and Xishan of Wuxi. This category mainly included cities or their adjacent units. As mentioned above, these areas already had very high proportions of construction lands before 1990, as they were urban centers with significant populations and industry agglomeration in the early stage. With the increasing area of incremental construction lands located in suburban areas, land development was limited. Meanwhile, early land development reduced the ecological suitability level, so the subsequent expansion of construction lands did not contribute to extensive ecological stress. Taking the city proper of Suzhou as an example, the construction lands in this city expanded by merely 31 km^2, while the ecological stress level was 2.96, almost the lowest value determined among all units.

4. Discussion

Rapid, intensive urbanization and the spatial expansion of construction lands introduce significant ecological stress to regional eco-safety and sustainable development in various ways [64,65]. It is among the topics of focus for academics to indicate the processes and patterns of land use transitions by evaluating the ecological stress levels associated with land use changes, especially with the expansion of construction lands [19]. Although different attributes of construction lands influence the resulting ecological stress levels, including the amount, proportion, detailed type and concentration degrees of industries and populations, the location effect is receiving the most attention [66,67]. Aiming to determine the pattern of land use transitions based on the ecological stress levels related to the spatial distribution of construction lands, we proposed an improved approach to evaluate the ecological stress level from the perspective of the spatial distribution of incremental construction lands. Taking the economically developed and densely populated southern Jiangsu as the case, we carried out ecological process simulations to determine the spatial differentiation of ecological suitability, identified the spatially variable ecological stress levels associated with incremental construction lands based on their distributions, and recognized different zones by comparing the incremental construction land areas and the associated ecological stress levels.

To indicate the spatial differentiation of the ecological stress contributed by construction lands, it is essential to analyze the ecological suitability levels of different regions. In regions with higher ecological suitability levels, the presence of construction lands generally induces higher ecological stress levels [26,68]. Although various methods have been widely adopted to evaluate ecological suitability, we chose to study suitability from the perspective of maintaining the integrity of ecological processes, as unbroken ecological processes are of the utmost importance for the conservation of biodiversity and ecosystem services [27,33]. With the support of the GIS spatial analysis function, we constructed ecological process simulations with the help of the *MCR* model due to its superiority in combining GIS spatial analyses with map making and operability in the data preparation process [48]. Based on the identification of the sources and resistance surface, the potential ecological processes and zones with different ecological suitability levels in southern Jiangsu were revealed. The results indicated that the spatial differentiation of the indicated ecological suitability was basically consistent with the physical geography and ecosystem features. The spaces surrounding certain sources/targets were of higher ecological suitability levels, while the built-up areas of cities were less suitable. Suitable ecological zones appeared not only as patches, but also as corridors along suitable landscape patches, especially along some continuous rivers. The importance of these indicated corridors in maintaining regional ecological safety was revealed, as these corridors could increase the connectivity of patched ecological spaces [69,70].

The spatial expansion of construction lands was dramatic and showed significant spatiotemporal differences from the perspective of their amount and spatial locations. This result was consistent with the economic development and population inflows in terms of the analyzed stages, and the period from 2005 to 2010, when the construction lands expanded the most, was also the period with the fastest economic growth and greatest population agglomeration. Spatially, the relationship between construction land expansion and socioeconomic development was also highly positive. From the perspective of the associated ecological stress, construction lands in zones with higher ecological suitability levels brought more significant disturbances to the ecological processes and hence, contributed to higher ecological stress levels. Basically, the incremental construction lands corresponded to high ecological stress levels, and the average stress value was 3.81 with a maximum of 5.00, indicating that the spatial expansion of construction lands was not ecologically friendly on the whole. From a quantitative perspective, only a limited area of incremental construction lands was associated with low ecological stress levels. It is suggested that the spatial expansion of construction lands should be restricted in southern Jiangsu [71,72]. However, as the spatial location of incremental construction lands affected the ecological stress value, these regulations should be spatially variable. In this study, incremental construction lands associated with high ecological stress levels were widely distributed and were mostly concentrated in some regions along Taihu Lake and the Yangtze River. As strong interference with ecological processes occurs, construction concessions and ecological restoration should be conducted in these regions [73]. However, such regions were also the preferred areas for land development and industrial growth [36,74]. To balance the relationship between ecological protection and land development, construction lands should be expanded while trying to control the occupation of areas with the highest ecological suitability levels, especially those that form ecological corridors [73,75]. Existing construction lands with high ecological stress levels should be ecologically restored as they occupy strategic points or potential corridors of regional ecological processes [25,27].

As counties are the basic units of governmental regulation regarding land development in China, we further derived ecological stress results at the county level. Although the spatial differentiation of county-level units with different ecological stress levels was slightly variable among each stage, units with moderate-high and highest stress levels dominated the study. As confirmed by the above results, a large amount of incremental construction lands is associated with high ecological stress levels. Basically, units with high ecological stress levels were concentrated around Taihu Lake and along the Yangtze River, where the ecological suitability was higher than that in other regions [19]. As both the expansion amount and spatial distribution of construction lands were related to different ecological stress levels, we identified four types of zones by comparing their expansion areas and ecological stress levels with the corresponding regional average values obtained for the whole study area. The H-H zones had both greater construction land areas and higher stress values; thus, it is suggested that the expansion of construction lands in these zones be strictly controlled to decrease ecological disturbances. Moreover, this is also the focus of ecological restoration, as the presence of a large amount of incremental construction lands induces greater ecological stress. For the H-L zones, although the land development was also fast, the resulting ecological stress was relatively low. Therefore, further land development should be encouraged through supportive land policies. The L-H zones caused high ecological stress with limited incremental construction lands, so further land development in these zones should be moved to regions with low ecological suitability levels [68,76]. Although the ecological stress level of the L-L zones was also low, land development should also be restricted in these regions because they already have high proportions of construction lands. Further land development in these regions is highly likely to occupy ecologically suitable spaces and destroy regional ecological safety.

5. Conclusions

The ecological protection and expansion of construction land are both location related, and there are spatial conflicts between them. The ecological stress caused by construction lands differs spatially, and these differences are caused by both the spatial locations of construction lands and the location-related differentiation of ecological suitability. Aiming to promote sustainable development and coordinate the relationship between land development and ecological protection, with the help of the *MCR* model and ecological process simulations, we identified the spatial differentiation of ecological suitability levels. Then, we evaluated the ecological stress levels of incremental construction lands and county-level zoning regions based on the amount of and ecological stress level associated with local incremental construction lands during different stages of land use transitions. We conclude that the location of incremental construction lands significantly affects the ecological consequences associated with the spatial differentiation of ecological suitability. Basically, incremental construction lands located in ecologically suitable zones cause high ecological stress. As the indicated ecological suitability level is obtained through an ecological process analysis, the location-specific ecological stress level has an obvious influence on regional ecological safety from the perspective of maintaining ecosystem integrity. Both construction lands and ecological suitability are location specific, and we believe that location-oriented evaluations could provide an effective approach for determining the spatial patterns of land use transitions based on spatially differentiated ecological consequences. According to these results, location-specific suggestions regarding land use regulations could also be proposed, including suggestions for spatially precise ecological restoration and the spatial redistribution of incremental construction lands.

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Spatiotemporal Evolution of Entrepreneurial Activities and Its Driving Factors in the Yangtze River Delta, China

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Abstract: The purpose of this paper is to reveal the spatiotemporal evolution of entrepreneurial activities in the local municipalities of the Yangtze River Delta at long timescales from a geographic perspective and to reveal the underlying factors driving such evolution. The ontology of entrepreneurial activities—startups—was chosen as the object of this study, and the developmental characteristics of entrepreneurial activities in the region since 2001 were explored in two dimensions: time series changes and spatial evolution. The driving mechanism was further explored using the geographical detector. The results showed that: (1) Intensive entrepreneurial activities have been underway in the Yangtze River Delta since the beginning of the 21st century. The entrepreneurial process has undergone a stable period of slow growth (2001–2013), as well as one of rapid growth (2014–2018). The number of startups increased during this period, from 241,700 in 2001 to 1,959,600 in 2018. (2) The density of entrepreneurial activities in the Yangtze River Delta has increased since 2001. The agglomerative patterns showed developmental trends of both concentration and diffusion, forming a dotted pattern of agglomeration centered on the provincial capitals of Nanjing, Hangzhou, and Hefei and a belt of agglomeration centered on Shanghai-Suzhou-Wuxi-Changzhou. (3) High-value agglomeration of entrepreneurial activities was found to be relatively stable, and low-value agglomeration steadily weakened. Shanghai, Suzhou, and Nantong have long been part of H-H clusters, while Chizhou, Wuhu, Bozhou, Huaibei, and Huainan in Anhui have become areas of depressed entrepreneurial activities. (4) Financial strength, degree of informationization, economic foundation, innovative vitality, openness, and market demand are the main factors affecting entrepreneurial activities in the Yangtze River Delta. Entrepreneurial activities have significant spatial correlation, and areas with high entrepreneurial vitality radiate their effect to the entrepreneurial activities in the surrounding areas. The factors affecting entrepreneurial activities have multiple characteristics, and policy makers should promote entrepreneurial activities with a comprehensive vision and multi-channel efforts. The findings of this study add to the understanding of the spatial proximity characteristics of long time series of entrepreneurial activities at the municipal scale in developing countries and reveal the characteristics of the multi-factor combinations affecting them.

Keywords: entrepreneurial activity; startup; spatiotemporal variation; driving factor; Yangtze River Delta

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1. Introduction

With the steady promotion of the entrepreneurial model of economic growth, which is characterized by resource regeneration, productivity development, and the implementation of innovation-driven development strategies, entrepreneurial activities have emerged as a major means of improving the quality and efficiency of economic growth as part of China's development as an economic powerhouse. Entrepreneurial activities can promote changes in the market structure and adjustments to the industrial structure, increase the supply of goods, and accelerate the development of emerging industries. Moreover, they can enhance microeconomic vitality, drive employment, increase residents' incomes, and promote orderly social mobility as well as fairness and justice in socioeconomic development [1–3]. They are thus an important force for promoting national and regional competitiveness. Technological development, accelerating the pace of technological integration into the economy, and comprehensive industrialization pose daunting challenges for China in the process of economic and social transformation and development [4]. Mature large and medium-sized enterprises face high sunk costs as well as institutional costs in the process of transformation and development. Entrepreneurial activities can accelerate technological innovation and transformation, and such activities led by startups form an important part of China's current reform and development program [5]. Therefore, promoting entrepreneurial activities is important for building an innovative economy and promoting sustainable development.

Academia has been paying attention to entrepreneurial activities for a long time. In particular, since the dawn of the 21st century, innovation and entrepreneurial activities, as the driving forces of economic growth, have emerged as the core elements of productivity across the world due to the advent of the knowledge economy and information age led by the Internet and Information Technology [6–8]. Scholars have systematically explored entrepreneurial activities, including the environmental factors affecting them [9,10], the effects of entrepreneurial activities [11], the relationship between regional development models and entrepreneurial activities [12,13], entrepreneurial policies [14], the spatial distribution of entrepreneurial activities and their locational characteristics [15–19], and the interactive relationships between entrepreneurial activities and the evolution of local industrial clusters [20]. The results have provided an important reference for follow-up studies. Different disciplines focus on entrepreneurial activities with different emphases. Geographical studies focus on the occurrence and development of social phenomena from a spatial perspective [21]. However, previous studies of entrepreneurial activities have tended to focus on specific regions as containers in which entrepreneurial activities can occur, ignoring the spatial dependence or spillover effects of entrepreneurial activities on a continuous geographical scale [19]. Discussion of the factors affecting entrepreneurial activity has more often than not focused on a specific regional factor, and analysis of the impact of regional factor combinations on entrepreneurial activity from an integrated perspective is still limited and sketchy [5]. In terms of research objects, current studies have focused mostly on a single company, a certain type of industry, or a platform for entrepreneurial activities [21], and have largely ignored their overall characteristics. In the time domain, most studies have focused on entrepreneurial activities in a single year, or within a short interval [22]. In the context of spatial and geographical scales, most studies have focused on developed countries and have overlooked developing countries [23]. Such research has usually focused on a given country, province, or city and has ignored urban agglomerations or integrated regions [24].

As China's economy has moved from the stage of rapid growth to one of high-quality development, increasing attention has been paid to entrepreneurial activities [25]. In 2015, China issued the "Guiding Opinions on the Development of Makerspace Space to Promote Mass Innovation and Entrepreneurship" in order to promote entrepreneurial activities in a holistic manner so as to support China's economic growth. The Yangtze River Delta is one of China's most active areas of economic development, and one of its most open and innovative regions [26]. It has a strong industrial foundation, prominent advantages in terms of science and education, and a healthy entrepreneurial atmosphere. Moreover, the integrated development of the Yangtze River Delta has become part of China's national development strategy, and its entrepreneurial vitality occupies a pivotal strategic position in supporting the overall state of China's modernization on its path to transformation and development.

As a whole, the Yangtze River Delta is one of the regions in China with the highest level of economic development, but the level of economic development within it is uneven, with Shanghai being the core of regional development, while Anhui Province, most of Zhejiang Province, and the northern part of Jiangsu Province belong to the periphery of the region in terms of economic development and entrepreneurial conditions [25].In terms of entrepreneurial dynamism, does this "core-edge" spatial structure still exist in the Yangtze River Delta? Can the Suzhou-Wuxi-Changzhou city belt, which is close to Shanghai, receive the high-quality entrepreneurial and innovative resources radiated from Shanghai effectively and maintain strong entrepreneurial vitality? As the most developed segment in China and the most entrepreneurially dynamic region, what are the characteristics of the factors affecting entrepreneurial activity in the Yangtze River Delta? Does the level of regional development play a dominant role in entrepreneurial dynamism? This series of problems are expected to be solved in this paper, and the authors expect that the solutions to the above problems will provide a reference for future decision-making in relation to entrepreneurial policy formulation and institutional optimization in the Yangtze River Delta, as well as provide relevant experience for the development of entrepreneurial activities in other regions of China.

Based on the above background, the purpose of this studies was to extract the data of all startups between 2001 and 2018 from the database of industrial and commercial enterprises, spatialize the startups according to their latitude and longitude, reveal the spatially divergent characteristics of entrepreneurial activities and their correlation characteristics at the municipal scale in the Yangtze River Delta, over the past 20 years with the help of exploratory spatial analysis methods from a geographic perspective, and explore the comparative characteristics of the different factor combinations affecting entrepreneurial activities in this region by way of single-factor analysis and two-factor interaction analysis using the geographical detector. The originality of the study is reflected in how it reveals the spatial proximity characteristics of entrepreneurial activities over long time scales at the city scale and the characteristics of the multi-factor combinations that affect entrepreneurial activities.

This paper is divided into six sections. The first part is an introduction; followed by a literature review; the third part introduces the case study area, research data and research methodology; the fourth part analyzes the evolutionary characteristics of entrepreneurial activities in the Yangtze River Delta in terms of their development history and spatial concentration and further explores the factors affecting them; the fifth part presents a discussion of the results; and finally, the sixth part summarizes the conclusions and suggests several policy implications.

2. Literature Review

The contribution of entrepreneurial activities to economic growth has been verified in various ways in the literature in different contexts, in both theoretical and positivist studies [27–30]. However, there has not been a uniform and appropriate understanding of which factors affect the development of entrepreneurial activities most significantly [31]. In the literature from different disciplinary backgrounds, researchers have proposed different ideas about the factors affecting entrepreneurial activities.

Entrepreneurial activities cannot be carried out in isolation from the specific entrepreneurial environment, and the social environment is also considered to be an important factor, including the elements of social values, customs, ethical perceptions and local culture [32]. A study of 54 regions in Europe found that regions with more positive attitudes toward entrepreneurship had higher entrepreneurial vitality [33]. Using the research framework of institutional economics, Alvarez et al. [34] analyzed how regional environmental conditions affected entrepreneurial activities at the regional level in Spain according to the gender of the entrepreneur. By comparing two Swedish cities, Sabrina and Marina [35] explored how regional culture based on industrial heritage affected entrepreneurial activities in different regions. Daymard's study [36] of the impact of gender bias on entrepreneurial activities finds that bias against women in India inspired the growth of some female entrepreneurs. In addition, a good social governance environment, such as a solid legal framework, a clear property rights system, clear and simple entrepreneurial procedures and other institutional conditions, also had a positive impact on entrepreneurial activities [37,38].

In addition to the entrepreneurial environment, many other factors, such as innovation, age, education level, entrepreneurship, business dynamics, financing conditions, openness and public policies, have an important impact on the development of entrepreneurial activities. Of these, innovative ability includes not only the ability to put innovative ideas into practice, but also the ability to learn new things, new processes, and new methods and to promote them into application, which is an important endogenous force for promoting entrepreneurship [39]. Gandhi et al. [40] analyzed the impact of demographic factors on entrepreneurial activity using individual-level data from the 2013 ASEAN National Entrepreneurship Consortium and found that early-stage entrepreneurs were generally more capable than mature entrepreneurs and that young entrepreneurs were generally more capable of starting a business. A questionnaire survey conducted by Borges et al. [41] for the northern region of Portugal found that education was a key element in promoting entrepreneurial motivation and that the better prepared students were for entrepreneurial activities, the more likely they were to become entrepreneurs. Entrepreneurial individuals have the initiative, creativity, and ability to take risks responsibly, and always interact positively with their environment in order to undertake successful entrepreneurial ventures [42]. Business vitality is an effective manifestation of market dynamics and competitiveness, which plays an important role in entrepreneurship, management, and the growth process of companies [43]. Funding is the cornerstone of entrepreneurial activities. Studies in Asia have found that financing conditions have a significant positive role in promoting entrepreneurial activities [44]. In the face of the opening of the global market, more efficient foreign companies can break into the domestic market. In such instances, there is the risk of foreign multinational companies monopolizing the domestic market and so the entrepreneurial vitality in corresponding fields is suppressed [45]. Salman's study [46] of countries with either efficiency-driven or innovation-driven development found that public policies to support entrepreneurial activity played an important role by improving education levels, strengthening research investment, and formulating attractive tax policies.

The conclusion to be drawn, therefore, is that previous studies of entrepreneurial activities have focused mainly on economics, management, and the social sciences, while the development of entrepreneurial activities is a process characterized by spatiotemporal constructs. Although the above-mentioned fields of studies provide a relatively solid disciplinary foundation, there is still a need to strengthen research on the spatiotemporal manifestations of entrepreneurial activities and the role played by spatiotemporal elements in their dynamic evolution [30]. Thus, there needs to be more of a geographical focus on the spatiotemporal dynamic differences in entrepreneurial activities in order to highlight geography's unique contribution to research in the field of entrepreneurship.

3. Materials and Methods

To reveal the spatiotemporal evolution of entrepreneurial activities and its driving factors in the Yangtze River Delta, the analytical framework was built. The authors analyzed the evolutionary characteristics of entrepreneurial activities in the Yangtze River Delta in terms of their development history and spatial concentration, and further explored the factors affecting them. The detailed research diagram is shown in Figure 1.

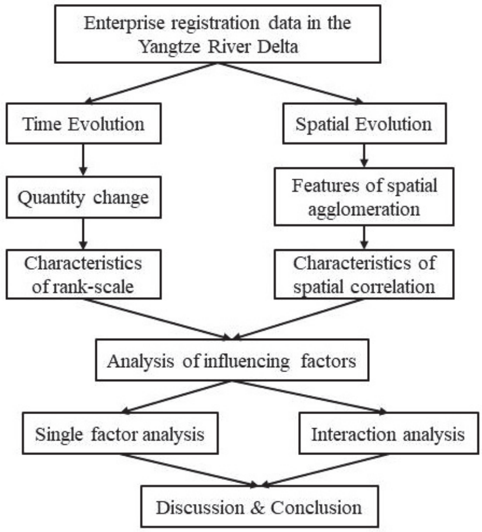

Figure 1. Technology roadmap for this study.

3.1. Study Area

The scope of the Yangtze River Delta region considered in this study was determined based on the "Outline of the Yangtze River Delta Regional Integration Development Plan" announced by the Chinese Central Government in 2019. It contains 41 cities in Shanghai, Jiangsu Province, Zhejiang Province, and Anhui Province (Figure 2) and covers an area of 359,100 km^2, accounting for 3.73% of China's total land area [47]. The Yangtze River Delta is in the plains of the middle and lower reaches of the Yangtze River. The southern part of Anhui Province and most of Zhejiang Province are hilly areas. The topographical conditions have shaped the spatial pattern of the delta, with a large population in the north and a small one in the south. It is among the strongest economic regions in China, with the highest population density and the largest number of towns. In 2019, its gross domestic product was CNY 23.73 trillion, accounting for 24% of China's gross domestic product, and its permanent population was 219 million, accounting for 15.7% of the country's total population [47]. The Chinese central government has identified the integrated development of the Yangtze River Delta region as part of its national development strategy, and its entrepreneurial activities and economic vitality have become distinctive indicators of China's economic development.

3.2. Data Sources

Data for the startups investigated in this study were taken from the Industrial and Commercial Enterprise Registration Database, which included information such as the name, office address, registered address, industrial classification, type of company, date of registration, registered capital, and geographic coordinates of each startup established in each year in China from 2001 to 2018. Four typical years, 2001, 2008, 2015, and 2018, were selected to carry out specific comparative time–space analyses. ArcGIS software was used to calibrate and transform the geographic coordinates of each startup in the database and establish a spatial point database of startups in the delta region. The relevant socio-economic data were taken from the statistical yearbooks of the three provinces and one city in the region and the statistical yearbooks of each city. Data for the administrative boundaries of the relevant provinces and cities were taken from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 25 November 2021)

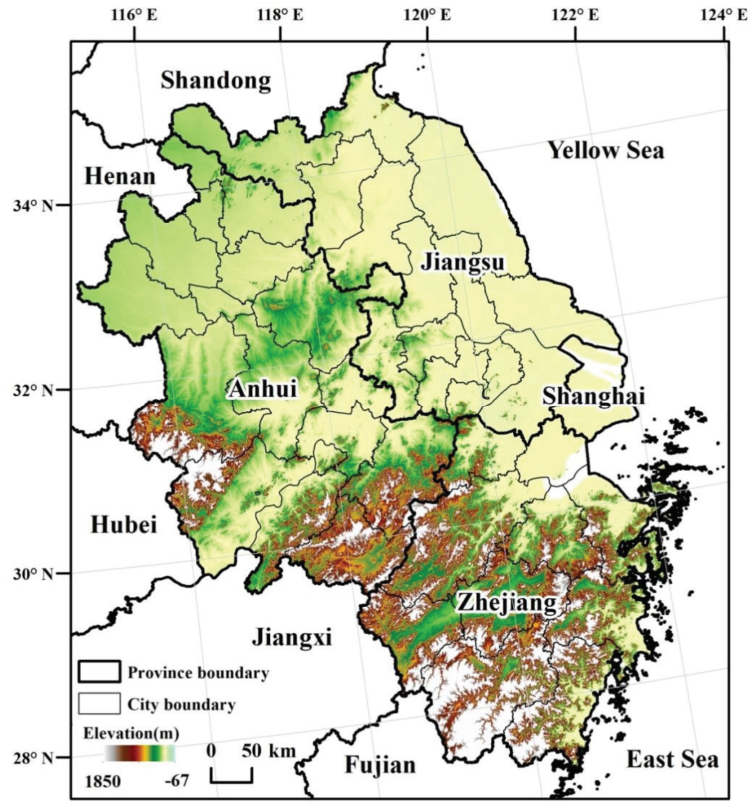

Figure 2. Geographic location of the Yangtze River Delta in China.

3.3. Research Methods

3.3.1. Rank-Scale Rule

The rank-scale rule is a method used in urban geography to explore the regular relationship between the scale of a city and its rank [48]. We used it to construct a rank-scale rule based on the number of startups:

$$P_i = \frac{P_1}{R_i^q} \tag{1}$$

$$\ln P_i = \ln P_1 - q \ln R_i \tag{2}$$

where P_i is the number of startups owned by cities in the research area of the order of i, R_i is the order of the i-th city, P_1 is the number of startups in the city with the most startups in the study area, and q is the slope of the regression line. The larger the value of q is, the more concentrated is the scale distribution of startups. The smaller the value of q is, the more balanced is the distribution of startups. The number of startups in small and medium-sized cities was larger.

3.3.2. Kernel Density Estimation

Kernel density estimation is a non-parametric method of estimation to describe the overall distribution of random variables [49]. We used it to describe the spatial agglomeration of startups in the Yangtze River Delta:

$$f_h(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x - x_i}{h}\right) \tag{3}$$

In the formula, $f_h(x)$ is the kernel function, h is bandwidth, n is the total number of startups, $(x - x_i)$ is the distance between the observation point x and the sample point x_i, and k is the density function. The kernel function calculates the agglomeration of point elements in the entire study area based on the input data. The larger the value of $f_h(x)$ is, the denser the distribution of points.

3.3.3. Spatial Correlation Analysis

Spatial autocorrelation is among the most important characteristics of geographic phenomena. It refers to the feature that the attribute value of an area adjacent to the observation unit is often similar to or different from the attribute value of an observation unit compared to that of a distant area. Spatial autocorrelation includes global and local autocorrelations. Moran's I and the Local Indicator of Spatial Association (LISA) can be used to explore the global and local correlations of regional units [50]. The spatial correlation characteristics of entrepreneurial activities are the highlight of this study, and also make up for the lack of existing research that ignores the spatial dependence or spillover effects of entrepreneurial activities in a continuous geographic range. The spatial autocorrelation method can express the spatial proximity characteristics of geographical phenomena effectively, which has been widely confirmed in existing studies [26,32,49] and is a suitably effective method for the purposes of this paper. We used the queen's rule to define the matrix of spatial weights, that is, regions with common boundaries or common vertices were defined as being adjacent to each other.

3.3.4. Geographic Detector

Geographical detectors are an effective method for exploring the mechanism of spatial heterogeneity for multiple independent variables covariance immunity, effectively overcoming the limitations of traditional econometric statistical methods, and can explore the spatial heterogeneity of factors without too many assumptions [51]. Factor detectors can be used to identify the effects of different factors on the spatial distribution of certain types of phenomena. Their unique ability to detect factor interaction can further explore the effects of different combinations of elements on the phenomenon being investigated. The single-factor detection and factor interaction detection functions of the geographic probe are in line with the purpose of this paper in order to carry out an analysis of the combined effects of factors affecting entrepreneurial activities. Established studies have confirmed it to be an effective method for revealing the driving mechanisms of geographical phenomena [52]. We used the factor detection part of the geographic detector to explore the relationship between the number of startups Y and the factors affecting them, X, in the Yangtze River Delta:

$$q = 1 - \frac{1}{N\sigma^2}\sum_{h=1}^{L} N_h {\sigma_h}^2 \tag{4}$$

where q represents the decisive power of the influential factors on the spatial differentiation of entrepreneurial activities, N and N_h represent the number of startups in the research area and their level h, σ^2 and ${\sigma_h}^2$, respectively, represent the variance of the number of startups in the study area and that of the number of startups in layer h, and L is the number of categories of variable X.

4. Results

4.1. Changes in Time Series of Entrepreneurial Activities

4.1.1. Overall Quantitative Changes

Since the beginning of the 21st century, entrepreneurial activities in the Yangtze River Delta have been intense, and the number of startups has grown exponentially (Figure 3). From 2001 to 2018, the number of startups in the region increased by more than seven times in 18 years, from 241,700 to 1,959,600. From the perspective of growth, entrepreneurial activities in the Yangtze River Delta have undergone a stable period of slow growth (2001–2013), followed by one of rapid growth (2014–2018). The development of entrepreneurial activities is closely related to the macroeconomic background and relevant national policies. The average annual growth of startups during the stable period was maintained at approximately 50,000, and the average annual number of entrepreneurs was maintained at approximately 400,000 from 2004 to 2007. There were no significant changes in successive years, and entrepreneurial activities were quite weak during this period. Since 2009, the number of startups has increased significantly because the Yangtze River Delta has gradually emerged from the effects of the 2008 global financial crisis. Due to the national policy on innovation, entrepreneurial activities in the region entered a period of rapid growth after 2014, with an average annual addition of 200,000 startups. The entrepreneurial wave of "mass entrepreneurship and innovation" advocated by central government has provided a favorable environment for entrepreneurship in the area. Additionally, provinces and cities in the Yangtze River Delta have applied for various platforms for entrepreneurial innovation. In the three batches of national-level crowd-creation space lists recognized by the Ministry of Science and Technology from 2015 to 2016, a total of 245 companies were approved in the Yangtze River Delta region. This has provided a strong impetus to entrepreneurial activities in electronic information, smart hardware, biomedicine, and cultural creativity. The implementation of the relevant policies has greatly stimulated the entrepreneurial vitality of the Yangtze River Delta.

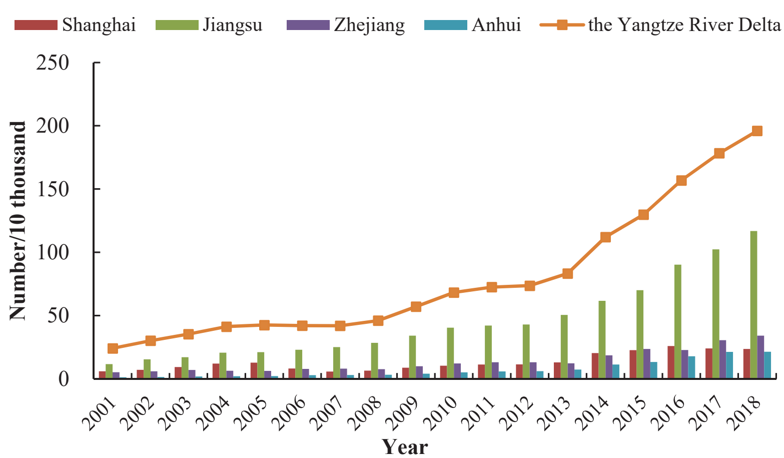

Figure 3. Changes in the number of startups in the Yangtze River Delta from 2001 to 2018.

There are significant regional differences in entrepreneurial activities across provinces and cities in the Yangtze River Delta. Jiangsu Province ranks first in terms of the number of startups, and its share of the total has increased from 48.26% in 2001 to 59.61% in 2018. Zhejiang Province ranks second, with an increase from 52,400 startups in 2001 to 341,300 in 2018, about 18% of the total. The number of startups in Shanghai has continued to grow, but its ratio of the total has continued to decrease from 24.68% in 2001 to 12.05% in 2018. Anhui Province has the smallest number of startups among the three provinces and one city in the Yangtze River Delta, but its entrepreneurial vitality has continued to increase in the past 18 years. Its ratio of startups to those in the Delta has increased from 5.39% to 10.93%.

4.1.2. Characteristics of Rank-Scale

The scale of startups in cities in the Yangtze River Delta region conforms to the typical rank-scale rule. Over time, the rank-scale characteristics have developed from those of concentration to those of greater balance, and the scale of startups in small and medium-sized cities continues to increase. A diagram of the rank-scale distribution (Figure 4) shows that the goodness of fit of each annual curve is above 0.83, which conforms to the typical rank-scale rule. The rank-scale structure presents a state of coexistence of low head and crunching. Shanghai, Suzhou, Nanjing, and Wuxi have long been at the top of the curve of the rank-scale, and have a large number of startups. However, the top-ranking cities in terms of the number of startups were all below the fitting curve, indicating their characteristics of scale were not well developed. The tail was mainly formed by Chizhou, Huaibei, Huainan, Huangshan, and Tongling in Anhui. These cities were in areas with poor economic development in the context of the region, and had limited funds, resources, and policies needed to support entrepreneurial activities. From the perspective of temporal evolution, the slope of the curve of fitting of the rank-scale has continued to increase from −1.4776 in 2001 to −1.2605 in 2018. The rank-scale characteristics have continued to develop from a state of concentration to equilibrium, indicating that over time, the concentration of entrepreneurial activities in the Yangtze River Delta region has been weakening in the top ranking city, while the entrepreneurial vitality of small and medium-sized cities has continued to increase.

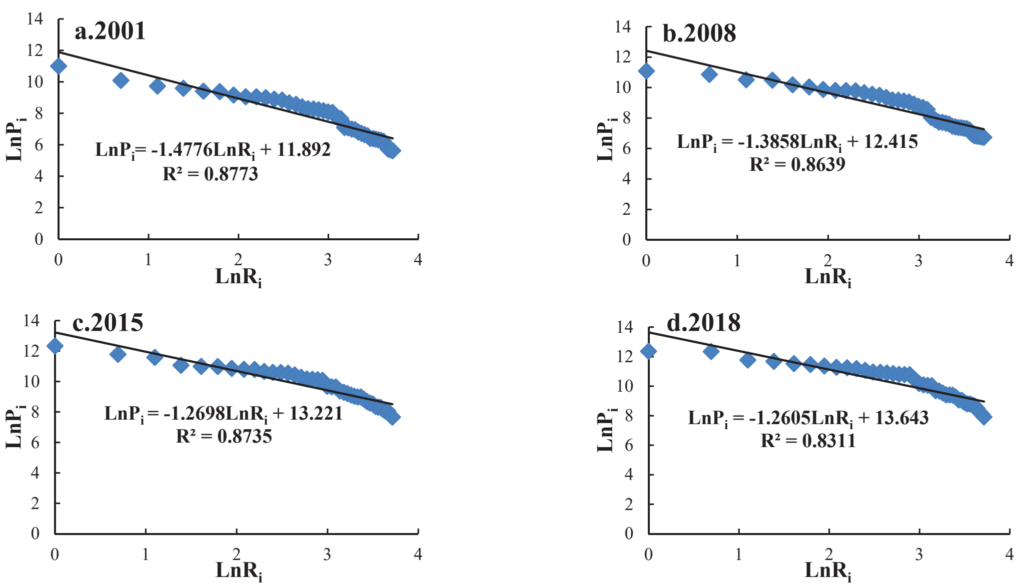

Figure 4. The rank-scale distribution of cities in the Yangtze River Delta defined by the number of startups (**a**) in 2001, (**b**) in 2008, (**c**) in 2015, and (**d**) in 2018.

4.2. Spatial Evolution of Entrepreneurial Activities

4.2.1. Features of Spatial Agglomeration

We applied data for the location of the startups to kernel density estimation in order to assess their spatial agglomeration characteristics in the Yangtze River Delta from 2001 to 2018 (Figure 5). Overall, since 2001, the spatial density distribution of startups in the region has been increasing, and their state of agglomeration has shown a developing trend in terms of both concentration and diffusion. While they form a dotted area centered on the provincial capital cities of Nanjing, Hangzhou, and Hefei, and a contiguous high-density strip in Shanghai-Suzhou-Wuxi-Changzhou, their range of spatial agglomeration represents a trend of spreading from the core to the peripheral areas, and from large to small and medium-sized cities.

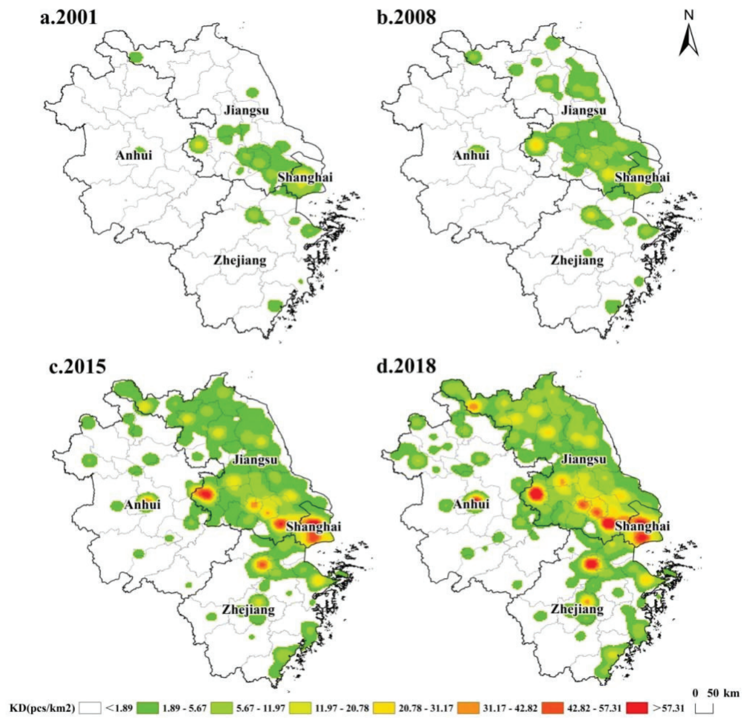

Figure 5. The spatial agglomeration status of start-ups in the Yangtze River Delta (**a**) in 2001, (**b**) in 2008, (**c**) in 2015, and (**d**) in 2018.

The peak spatial density distribution of startups in the Yangtze River Delta from 2001 to 2018 increased from 20.78 per km^2 to 84.95 per km^2. High-density areas continued to expand, and areas with densities below 1.89 pcs/km^2 continued to shrink. The density distribution exhibited spatial patterns of high in the north and low in the south, and high in the east and low in the west. The spatial density distributions of Jiangsu and Shanghai continued to increase, and high-density areas showed an overall development trend. However, Anhui and Zhejiang were restricted by the level of economic development and the geographical environment, respectively. High-density areas were dotted throughout the region as a whole, and the entire area was dominated by low-density areas. From the perspective of spatial agglomeration, the provincial capitals of Nanjing, Hangzhou, and Hefei underwent large increases in their densities in 18 years to form dotted areas of agglomeration for entrepreneurial activities. Shanghai, Suzhou, Wuxi, and Changzhou are not only geographically adjacent to each other, but the spatial densities of their startups were also the highest in the region, forming a belt-shaped high-density area of concentration. Entrepreneurial activities were concentrated in major cities, and the density of startups in cities with strong economic vitality in the periphery increased during the period of study, with several regional dense cores appearing. Xuzhou in the north of Jiangsu Province, Jinhua in central Zhejiang Province, Ningbo in the east, and Wenzhou in the south all recorded increased densities. This overall pattern reflects the development of entrepreneurial activities in cities at different levels of development in the Yangtze River Delta.

4.2.2. Characteristics of Spatial Correlation

The entrepreneurial activities of cities in the Yangtze River Delta have shown significant characteristics of spatial correlation. From 2001 to 2018, values of the Global Moran's I index of the four cross-sectional startups in the region were all greater than zero, and their *p*-value was all less than 0.01, thus passing the significance test at the 1% level. This shows that entrepreneurial activities of cities in the Yangtze River Delta have shown a significant positive spatial correlation; that is, high-high and low-low characteristics of agglomeration of entrepreneurial activities have been observed (Table 1). From the perspective of temporal evolution, Moran's I index showed increased volatility, indicating that the characteristics of spatial correlation of entrepreneurial activities in the Yangtze River Delta have shown a trend of increased volatility.

Table 1. Global Moran's I of startups in the Yangtze River Delta from 2001 to 2018.

Year	2001	2008	2015	2018
Moran's I	0.2463	0.3858	0.2558	0.3516
Z-Score	3.3230	3.8785	2.9062	3.5444
p-Value	0.0009	0.0001	0.0037	0.0004

As shown in Figure 6, the clustering obtained using LISA at the prefecture-level city-scale revealed high-value and low-value agglomerations of entrepreneurial activities in some regions of the Yangtze River Delta. High-value agglomeration in the region was relatively stable, while low-value agglomeration gradually weakened. The number of H-H clusters was relatively stable, at approximately three. The number of L-L clusters gradually decreased from seven in 2001 to one in 2018, and the numbers of H-L clusters and L-H clusters were relatively small. From the perspective of the connections formed by each city, Shanghai, Suzhou, and Nantong have long belonged to H-H clusters. Shanghai is a municipality directly under the control of the Central Government of China and is the country's center of economic, financial, trade-related, and technological innovation. It is economically strong, and has an excellent environment for entrepreneurship and innovation. It also has the highest entrepreneurial vitality in the Yangtze River Delta. Suzhou and Nantong are adjacent to Shanghai, and their economic development and technological innovation are driven by it due to the spillover effect of Shanghai's developmental resources. Chizhou and Wuhu in southwest Anhui and Bozhou, Huaibei, and Huainan in northwest Anhui lag behind other parts of the region. They have limited degrees of innovation, few entrepreneurial platforms, and imperfect policy support. These areas thus have depressed entrepreneurial activities, and are classed as L-L agglomeration areas. Hefei, the capital of Anhui Province, and Hangzhou, the capital of Zhejiang Province, have gradually developed into H-L clusters because economic development in provincial capital cities is generally at the forefront of each province's development. At the same time, these cities enjoy advantageous resources in terms of politics, talent, and technological innovation, and their entrepreneurial vitality is generally higher than that of surrounding cities. Jiaxing and Huzhou in Zhejiang Province are located between Shanghai and Hangzhou. As their developmental strength and entrepreneurial vitality are significantly lower than those of Shanghai and Hangzhou, they have depressed entrepreneurial activities, and an L-H agglomeration area.

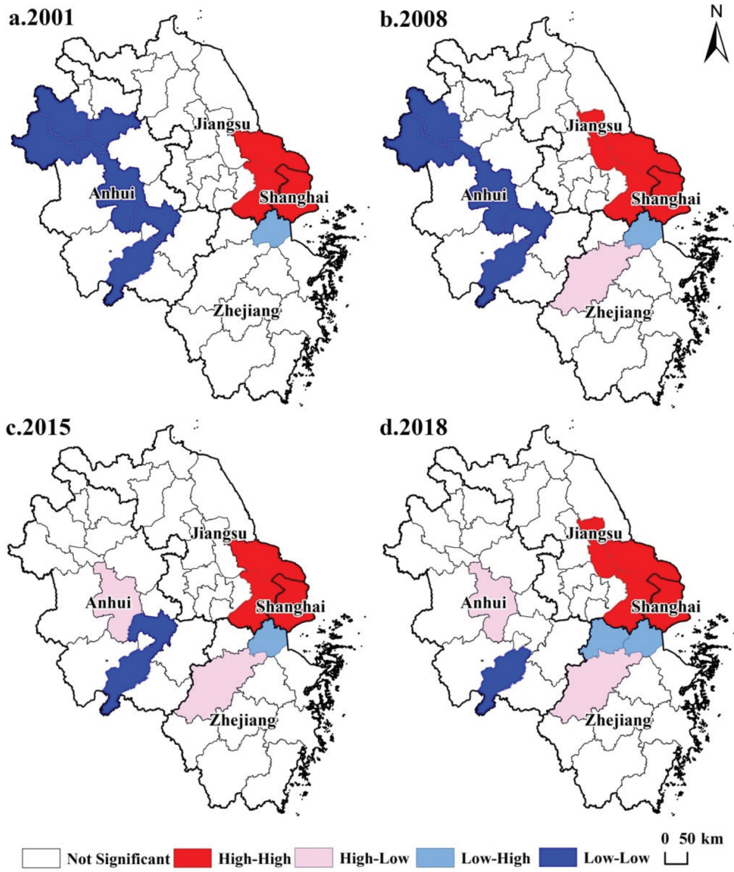

Figure 6. Map of LISA agglomeration of startups in the Yangtze River Delta (**a**) in 2001, (**b**) in 2008, (**c**) in 2015, and (**d**) in 2018.

4.3. Analysis of Driving Factors

4.3.1. Selection of Driving Factors

The development of entrepreneurial activities has strong regional roots and requires a suitable combination of various frameworks and systemic conditions conducive to entrepreneurship [53]. These include the level of regional economic development, the characteristics of the industrial structure, the degree of openness to development, the state of market demand, the degree of technological innovation, and the conditions of human capital [54–57]. Following scientific and systematic principles, and also those of objectivity and data availability, we used the per capita and proportional indicators as the factors affecting entrepreneurial activities in order to adequately reflect the impact of differences in the relative efficiencies of cities. Nine indicators were selected based on four aspects: economic development, degree of openness, social environment, and innovation-related conditions. Per capita GDP (X1) was used to characterize the economic foundation, the ratio of the output of tertiary industry (X2) was used to characterize the industrial structure, and the year-end loan balance of financial institutions per capita (X3) was used to characterize financial strength. The degree of openness was characterized by the total ratios of imports and exports to GDP (X4). The total number of postal and telecommunications businesses per capita (X5) was used to characterize the degree of informationization, total retail sales of consumer goods per capita (X6) was used to characterize market demand, and the density of the highway network (X7) was used to characterize the convenience of the transportation infrastructure. The ratio of employees at the end of the year (X8) was used to characterize the extent of available human resources, and the number of patents granted per 10,000 people (X9) was used to represent the vitality of innovation. Based on the statistical yearbooks of cities in the region in the relevant years, data on four typical years were obtained, and tools for factor detection and interactive detection in the geo-detector were used to explore the explanatory power of single factors as well as the characteristics of interaction on the entrepreneurial activities among various driving factors.

4.3.2. Single Factor Analysis

The results of the single-factor detection (Table 2) showed that over time, the factors affecting entrepreneurial activities in the Yangtze River Delta have gradually shifted from multiple to concentrated. Financial strength, degree of openness, degree of informationization, and market demand were the factors exerting the greatest effects. The economic foundation and industrial structure had low explanatory power, underwent fluctuations, and exhibited decreasing levels of significance in testing. Both indicators failed the test of significance in 2008 and 2018. The overall convenience of transportation, availability of human resources, and vitality of innovation failed the test of significance at the 10% level. Financial strength, degree of openness, degree of informationization, and market demand significantly affected entrepreneurial activities. The explanatory power of financial strength and the degree of informationization both increased, from 0.5982 and 0.5589 in 2001 to 0.6369 and 0.6428 in 2018, respectively. Although the explanatory power of market demand decreased during this period, its overall explanatory power remained high. The explanatory power of the degree of openness dropped significantly, from 0.7528 in 2001 to 0.2929 in 2018.

Table 2. Results of factors affecting entrepreneurial activities in the Yangtze River Delta.

Year	X1	X2	X3	X4	X5	X6	X7	X8	X9
2001	0.6404 ***	0.3331 *	0.5982 ***	0.7528 ***	0.5589 ***	0.8372 ***	0.1959	0.2151	0.5000 ***
2008	0.3242	0.2449	0.5306 ***	0.5442 ***	0.5686 **	0.5049 ***	0.1930	0.1204	0.1911
2015	0.2580 *	0.5332 ***	0.5981 ***	0.6941 ***	0.7197 ***	0.2785 *	0.1723	0.1148	0.1740
2018	0.4176	0.1977	0.6369 ***	0.2929 *	0.6428 ***	0.5356 ***	0.0650	0.2494 *	0.2205

Note: *, **, and *** indicate significance levels of 10%, 5%, and 1%, respectively. Per capita GDP (X1), the ratio of the output of tertiary industry (X2), the year-end loan balance of financial institutions per capita (X3), the total ratios of imports and exports to GDP (X4), the total number of postal and telecommunications businesses per capita (X5), total retail sales of consumer goods per capita (X6), the density of the highway network (X7), the ratio of employees at the end of the year (X8), the number of patents granted per 10,000 people (X9).

4.3.3. Interaction Analysis

From the perspective of two-factor interaction (Figure 7), the explanatory power of interactions between the influential factors was significantly higher than that of any single-factor. The types of interactions consisted of two-factor enhancement and nonlinear enhancement, with an equal number of instances of each. A single or single-type element controlled the spatial differentiation of entrepreneurial activities. The interaction between any pair of influential factors increased the explanatory power of spatial differentiation of their entrepreneurial activities. The occurrence and development of entrepreneurial activity requires an integrated combination of elements. Financial strength, degree of openness, and vitality of innovation had the most substantial effect on the interactions among other factors, indicating that financing, access to international markets, and level of innovation were essential elements affecting the development of entrepreneurial activities. Regulating the conditions of other factors based on the satisfaction of such factors had a magnifying effect on the promotion of entrepreneurial activity. The economic foundation and the degree of informationization also showed strong synergy with other factors, indicating that the local environment for economic development and the efficiency of circulation of knowledge and information had a catalytic effect on entrepreneurial activities. Enhancing the level of development of such factors can have a qualitative and efficiency-enhancing effect on entrepreneurial activity. In addition, interactions between industrial structure, market demand, and other factors led to enhancement, indicating that optimizing the economic structure, industrial upgrading, and a strong consumer market demand all had a positive impact on the development of entrepreneurial activities; its two-factor synergy was stronger than the explanatory power of a single factor.

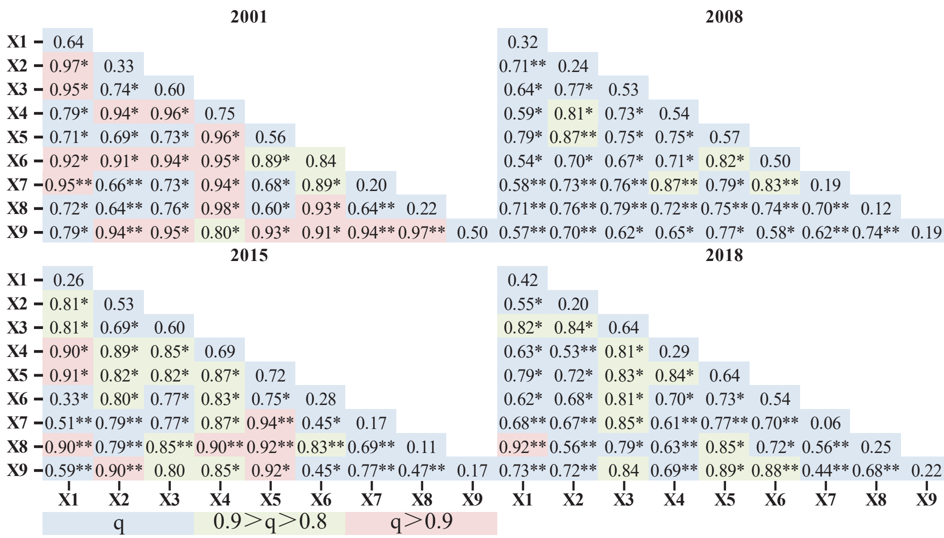

Figure 7. Results of interactions between factors influencing entrepreneurial activities in the Yangtze River Delta. Note: * and ** indicate “Enhance, bi” and “Enhance, nonlinear”, respectively. Per capita GDP (X1), the ratio of the output of tertiary industry (X2), the year-end loan balance of financial institutions per capita (X3), the total ratios of imports and exports to GDP (X4), the total number of postal and telecommunications businesses per capita (X5), total retail sales of consumer goods per capita (X6), the density of the highway network (X7), the ratio of employees at the end of the year (X8), the number of patents granted per 10,000 people (X9).

4.3.4. Analysis of Impact Mechanism

We used the above quantitative examination of the leading factors and their interactions as they affected entrepreneurial activities in the Yangtze River Delta in order to analyze the internal mechanism driving entrepreneurial activities. The aim was to provide a decision-making reference for creating a suitable external environment for “mass entrepreneurship and innovation”.

(1) Financial strength is the essential condition determining entrepreneurial activities. Funding is the cornerstone of entrepreneurial activities, and the basis for ensuring that all innovative thinking and ideas are transformed into material conditions. Funds to enable entrepreneurs to carry out their activities are usually provided as bank loans [58], and the year-end loan balance of financial institutions per capita is an important indicator of the regional financial environment, which can reflect the ease of obtaining financial support for entrepreneurial activities. The greater the financial strength, the looser the financial policy environment in the region, which helps entrepreneurs solve financial problems, obtain investments and other resources, and ensure the smooth development of entrepreneurial activities. In addition, the latter often emphasize entrepreneurial opportunities, and transforming new formats and ideas into a commercial format is an important means of achieving entrepreneurial success and maintaining a competitive edge. Therefore, strong financial support can

provide timely means to support entrepreneurial activities, which is a basic element for maintaining the vitality of regional entrepreneurship. Our study showed that financial strength has a high single-factor explanatory power for entrepreneurial activities and is generally conducive to the efficiency of the other driving factors.

(2) The degree of informationization is crucial in determining the level of entrepreneurial activities. The 21st century is the era of informationization and networking. For entrepreneurial activities in these times, the degree of informationization determines the ability of a region to utilize and deploy resources. The greater the number of postal and telecommunications businesses per capita, the more developed regional informationization is, and the greater the investment in informationization. A high level of informationization is not only conducive to accelerating the efficient circulation of knowledge and the other elements of innovation and promoting the flow and dissemination of entrepreneurial resources through social networks but is also conducive to local entrepreneurs getting a timely and practical grasp of the relevant regional policies and market information so that they can share off-site sources of entrepreneurship and innovation. This can also optimize the incubation of the local entrepreneurial platform and policy environment, making the area suitable for sources of information and entrepreneurial innovation. The degree of informationization has increasingly fluctuated in its effects on the entrepreneurial activities in the Yangtze River Delta. The single-factor explanatory power rose from 0.5589 in 2001 to 0.6428 in 2018. Interactions with other factors also showed strong synergistic determinism.

(3) Economic foundation and vitality of innovation are synergistic factors affecting entrepreneurial activities. The former reflects the overall developmental environment of a given place: the higher the level of economic development, the better the overall developmental environment of a region and the better the conditions for obtaining various advantageous resources. However, this does not imply a higher level of entrepreneurship. Studies have confirmed that, with increasing levels of economic development in developing countries, entrepreneurship has not shown the same trend of substantial increase. However, with the growth of large and medium-sized enterprises, the rapid development of regional economics can provide more employment opportunities. A continual rise in wages motivates potential entrepreneurs to avoid risks and choose employment [58]. In addition, the vitality of innovation represented by the number of patents granted per 10,000 people did not have a strong explanatory power for entrepreneurial activities in the Yangtze River Delta region, because regions with a strong vitality of innovation struggle to implement entrepreneurial activities owing to widespread problems in the developmental environment or insufficient entrepreneurial support, such as a lack of funds. These results indicated that only when the overall level of regional development is high, the vitality of innovation is solid and other factors are simultaneously available do all these factors play a synergistic role in promoting entrepreneurial activities.

(4) Openness and market demand also promote entrepreneurial activities. The element of transparency, characterized by the ratio of total foreign trade imports and exports to GDP, reflects the level of openness of regional development to international markets. The higher the degree of opening up, the more conducive the given region is to expanding the consumer market for local products. Harmony with the global market is conducive to the dissemination and spillover of new knowledge, technologies, and formats, provides potential local entrepreneurs with new ideas and skills for entrepreneurship, and enhances its vitality. The total retail sales of consumer goods per capita reflects the dynamism of the regional economy and the level of consumption and also represents regional market demand. The higher the market demand, the stronger the vitality of the regional economy, the more frequent the circulation of factors, the more urgent the need for new products and technologies, and the stronger the promotion of innovation and entrepreneurial activities. We found that the impact of regional openness and market demand on entrepreneurial activities in

the study area passed the 10% significance test. The indices of the explanatory power of openness and other factors in 2001 and 2015 were all above 0.8.

5. Discussion

5.1. Comparison of Spatial Differentiation in Entrepreneurial Platforms and Activities

The occurrence and development of entrepreneurial activities are influenced and guided by policies, platforms, the development environment and other conditions. Moreover, the essence of entrepreneurial activities is spontaneous market behavior, whose spatial distribution exhibits a certain randomness owing to a large volume of data relating to regional entrepreneurial activity. However, few platforms are available for entrepreneurial innovation in various regions and are thus easy to extract and describe. Academic research has paid little attention to entrepreneurial activities, and many researchers have chosen platforms for entrepreneurial innovation as the objects of their research. Although these platforms play an important guiding role in the spatial distribution of entrepreneurial activities, whether they can characterize their distribution effectively remains to be verified.

We compared the results of this study with those reported by Wei Sheng et al. [26], who used venture capital institutions and entrepreneurial platforms as research objects in the same region investigated in this study. Overall, the spatial layout of the latter was consistent with that of the startups. However, the local spatial layout of venture capital institutions was more consistent with the spatial distribution of startups than that of entrepreneurial platforms because the government had promoted the construction of entrepreneurial platform, while the layout of venture capital institutions was more a function of market behavior. The spatial distribution of venture capital institutions driven by market forces can more truly reflect startups' spatial distribution, which represents market behavior. In addition, the spatial distributions of both venture capital institutions and entrepreneurial platforms were relatively limited, and the promotion of entrepreneurial activities was more localized. In addition to the influence of institutions and platforms, entrepreneurial activities were affected by the overall development environment of the region. A region with an excellent entrepreneurial climate can yield spatial spillover effects in surrounding areas. The development of the Yangtze River Delta region, as influenced by the entrepreneurial environment of cities such as Shanghai and Suzhou, led to the formation of the high-density entrepreneurial cluster of Shanghai-Suzhou-Wuxi-Changzhou around it. The spatial spillover effect of entrepreneurial activities is difficult to reflect in the layout of entrepreneurial institutions and platforms.

5.2. Driving Mechanism of Entrepreneurial Activities Has Multiple Characteristics

Revealing the driving mechanism of regional entrepreneurial activities is conducive to formulating policies for enhancing regional entrepreneurial vitality. However, studies analyzing the driving mechanism of entrepreneurial activities have usually focused on a single factor while ignoring the interaction between other factors [20,32,58,59]. We used a geographic detector model to reveal the factors affecting the spatial differentiation of entrepreneurial activities in the Yangtze River Delta. Traditional single-factor detection was supplemented by interactions among elemental combinations for further analysis. The results showed that a variety of influential factors generally exhibited both dual-factor and non-linear enhancement, indicating that the combination of factors enhanced the explanatory power of the spatial differentiation of entrepreneurial activities. That is, the driving mechanism of entrepreneurial activities had multiple characteristics. Therefore, future studies should pay attention to a comprehensive analysis of multi-factor combinations in order to guide the formulation of relevant policies and promote more comprehensive development of local entrepreneurial activities.

China is in transition from factor-driven to innovation-driven development, and the Yangtze River Delta region is one of the most economically developed regions in the country, whose entrepreneurial activities and economic vitality are distinctive signs of China's innovative economy. This study found that the year-end loan balances per capita of financial institutions showed strong explanatory power in both one-way analysis and two-way interaction, i.e., financial strength has played an extremely important and fundamental role in entrepreneurial activities in the Yangtze River Delta, a finding consistent with those of Lopes et al. [44] and Singh et al. [60] on entrepreneurial activities in Asia. This is due to the fact that starting or continuing a business in Asian countries often involves the cumbersome process of obtaining credit from financial institutions, and since finance is the cornerstone of entrepreneurial activity, the more lenient the financial conditions, the more favorable the entrepreneurial activity. In addition, regarding the impact of openness on entrepreneurial activity, a study by Lopes et al. [44] found that participation in globalization and the opening up of new markets leads to more efficient foreign firms stealing markets from a country, resulting in the formation of monopolies in the domestic market and reducing entrepreneurial dynamism in related industries. However, this paper reaches the opposite conclusion, namely, that greater openness is conducive to promoting entrepreneurial activity. This is because Lopes et al.'s study was conducted over a short time period, while this study was conducted over a long time range of nearly 20 years. Thus, the findings of these two differentiated studies on the impact of openness on entrepreneurial activity over short and long time periods, respectively further confirm De Backer et al.'s [45] findings that the entry of foreign capital and foreign firms may have a negative impact on entrepreneurial activity in the short term but have the opposite effect in the long term.

6. Conclusions

From the perspective of geography, this paper extracts the data for all startups from 2001–2018 from the database of industrial and commercial enterprises, reveals the spatially divergent characteristics of entrepreneurial activities and their correlation characteristics at municipal scale in the economically heavily developed Yangtze River Delta, over the past 20 years with the help of exploratory spatial analysis, and explores the characteristics of factor combinations affecting entrepreneurial activities in this region by means of single-factor analysis and two-factor interaction analysis using the geographical detector. Our study found that, since the beginning of the 21st century, entrepreneurial activities in the Yangtze River Delta have been intense and have undergone a stable period of slow growth (2001–2013), followed by one of dynamic, rapid growth (2014–2018). The growth trend of entrepreneurial activities was found to be closely related to the macroeconomic background and relevant national policies.

In the past 18 years, the spatial density distribution of startups in the Yangtze River Delta increased. The state of agglomeration of these startups showed developmental trends of concentration and diffusion, while forming a dotted pattern of agglomeration centered on the provincial capital cities of Nanjing, Hangzhou, and Hefei. The entrepreneurial activities of cities in the Yangtze River Delta exhibited significant characteristics of spatial correlation. Over time, the state of high-value agglomeration of entrepreneurial activities has become relatively stable, and the trend of low-value agglomeration has gradually been weakening. Financial strength, degree of informationization, economic foundation, vitality of innovation, degree of openness, and market demand are the main factors affecting entrepreneurial activities in the Yangtze River Delta. This study confirmed that entrepreneurial activities have significant spatial correlation and that areas with high entrepreneurial vitality have a radiating effect on entrepreneurial activities in neighboring areas. In addition, our study found that the factors affecting entrepreneurial activities are multifaceted and that policy makers should promote entrepreneurial activities through multiple channels from a holistic perspective. Our study adds to the understanding of the spatial proximity characteristics of long time series of entrepreneurial activities at municipal scales in developing countries and reveals the multi-factor combination of characteristics that drive entrepreneurial activities.

The spatial distribution of entrepreneurial activities in the Yangtze River Delta region remains uneven. Large cities have spatial imbalances, such as "shadow zone" of entrepreneurial activities. In the context of implementing the national development strategy of regional integration in the Yangtze River Delta region, particular attention should be paid to the following points in the future in order to promote the development of entrepreneurial activities: (1) There is a need to strengthen the leadership of central cities and expand their spillover effects. The development status of entrepreneurial activities in the Yangtze River Delta should be combined with those of the provincial capital cities of Nanjing, Hangzhou, and Hefei as well as the Shanghai-Suzhou-Wuxi-Changzhou metropolitan belt as cluster centers, with the aim of promoting the orderly spillover and dissemination of factors affecting entrepreneurial innovation, including talent, information, capital, and policies, in order to stimulate entrepreneurial vitality and economic potential in the surrounding regions and enhance the level of regional entrepreneurial and collaborative development. (2) The role of entrepreneurial platforms needs greater attention to be paid to it and the layout of the platforms needs to be optimized. Led by venture capital institutions and entrepreneurial platforms, full play needs to be given to the initiative of provincial governments in the overall deployment of resources. The layout of the platforms of entrepreneurial depressions in northern Jiangsu, southwestern Zhejiang, and northern Anhui needs to be addressed, and traffic corridors should be used to promote the construction of channels of entrepreneurial innovation, such as G60. An entrepreneurial network of platforms needs to be built in the Yangtze River Delta. (3) Entrepreneurial vitality needs to be strengthened, and there needs to be a greater ability to take advantage of scientific and technological achievements. The construction of a soft environment for policies, finance, services, and commerce in various regions needs to be strengthened in order to provide a suitable external environment for the growth and development of enterprises, to increase investment in technological research and development and cultivate high-tech talent, and to continue to inject renewed energy into entrepreneurial activities. An entrepreneurial system that integrates production, education, and research needs to be constructed in order to ensure proper connections among basic and applied research, industrialization, and innovation and entrepreneurship. (4) Central government needs to continue to open up the economy and use entrepreneurial activities to boost the dual-cycle developmental pattern. Under the leadership of the "Belt and Road" Initiative, an open regional economic system needs to be built, and the development opportunities afforded by open cooperation platforms such as the China International Import Expo need to be exploited in order to connect with overseas cooperation parks for the benefit of production. The development of entrepreneurial activities based on domestic and overseas markets or resources also needs to be promoted, in order to integrate them efficiently into the dual-cycle developmental pattern within China and across the world.

Since the acquisition of data for the latest year has not yet been implemented, the data have not been updated to 2020 due to objective reasons, which is a shortcoming, and therefore further supplementary studies will need to be conducted to update the data when new data become available. In addition, entrepreneurial activities involve many developmental stages, such as the birth, growth, evolution, and death of startups. Due to limitations of space, this paper has focused on entrepreneurial activities in their initial stages only, whereas their subsequent evolution is also important for their overall development. At the same time, the choice of spatial location for startups is an essential factor in the formation of industrial clusters, and profoundly affects their prospects for success. Future studies should also take into account the impact of startups' locations on the growth and death of enterprises. Since the end of 2019, the outbreak of the COVID-19 pandemic, which seriously affected the normal functioning of the social economy, was an abnormal stage in the evolution of entrepreneurial activities. The trends of entrepreneurial activities during and since the COVID-19 pandemic will be studied and refined in future research.

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How Should the Effectiveness of Marine Functional Zoning in China Be Evaluated? Taking Wenzhou Marine Functional Zoning as an Example

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Abstract: Marine functional zoning is a basic form of marine management proposed and organized by the Chinese government in the late 1980s, and the third round of planning and implementation has been completed. Effectiveness evaluation of marine functional zoning is an important tool to supervise the implementation of marine functional zoning and improve the level of marine management. For the first time, based on the concept of consistency, based on the planning blueprint, with the sea area use compliance, environmental quality compliance and development and utilization impact as the evaluation benchmark, this paper attempts to integrate and construct the coordination discrimination method of sea area utilization status and marine functional zoning, that is, the coordination index of marine functional zoning, and takes Wenzhou as an example. The research shows that the coordination index of marine functional zoning in Wenzhou is 0.81 during the planning period, and the implementation effect of marine functional zoning is good. Empirical research shows that this evaluation method can provide basic guidance for scientific compilation and effective implementation of marine spatial planning.

Keywords: marine functional zoning; implementation evaluation; blueprint; territorial space planning; Wenzhou

1. Introduction

Since the 21st century, the contradiction between the supply and demand of China's land resources has become increasingly fierce, resulting in the utilization of marine resources continuing to expand. The marine economy has grown into a new growth point of the national economy. However, the marine resource environmental bearing capacity is limited, and the unlimited use of coastal, island and sea areas will cause a series of marine environmental and economic problems (e.g., extensive and inefficient utilization of marine resources, increased environmental pollution, and ecosystem degradation). Therefore, sea area utilization needs scientific planning and guidance [1]. Marine functional zoning is an important tool for governments to optimize the utilization of marine resources and guide the sustainable development of the ocean by creating a spatial balance mechanism of marine utilization activities, coordinating the relationship between marine utilization demands and ecological environment protection, and seeking the harmonious development of marine resources and the environment and marine economy [2]. However, there is a problem of "emphasizing compilation and neglecting implementation" in China's existing marine spatial planning system, which makes it difficult for all marine spatial planning to give full play to the role of guiding marine economic activities [3]. Therefore, we constructed an evaluation method for the implementation of marine functional zoning and used Wenzhou City as an example to judge the coordination between the current sea area utilization and *Wenzhou Marine Functional Zoning (2013–2020)*, which lays a foundation for the compilation of the marine part of Wenzhou's territorial spatial planning and provides a reference for future planning implementation evaluations.

The ocean is a complex system of water, including the marine life that lives in it, the atmosphere above the adjacent sea surface and the coasts and seafloor that surround it. Due to the fluidity of seawater, the ocean system is often more dynamic, connected, stratified and integrated. This makes it difficult to obtain marine ecological environmental factor data, and with changes in the observation scale, the data accuracy and application range will change greatly. Therefore, it is obviously very difficult to evaluate the implementation process of marine functional zoning, which is not yet operable enough. Therefore, the implementation evaluation of marine functional zoning should focus on result evaluation and adopt planning blueprints or planning targets as evaluation reference standards [4]. In view of the availability of empirical case data, this paper attempts to build the coordination discrimination method of marine functional zoning for the first time, that is, the coordination index of marine functional zoning, from three aspects: Compliance of sea area utilization, compliance of environmental quality standards and impact of development and utilization, and based on the concept of consistency and planning blueprint, Wenzhou was taken as an example. On the basis of solving the practical problems of Wenzhou marine spatial division, this paper aims to provide theoretical ideas and solutions for the implementation evaluation of marine spatial planning around the world, and promote the sustainable, efficient and reasonable development of global marine ecology.

2. Literature Review

2.1. From Spatial Planning to Marine Spatial Planning

Spatial planning is based on the concept of European Union integration and sustainable development. It is the geographical expression of economy, policy, culture and ecology in the time section to solve spatial connection and coordination [5–7]. In the process of the literature review, it was found that the connotation and scale of spatial planning are constantly developing and updating. In the early stage of development, spatial planning was a macroscale regional development strategy, and Strategic Spatial Planning Approach is the first to put forwards the coordination framework of European urban and regional planning based on the traditional land planning level. The *European Spatial Development Perspective* (ESDP), promulgated in 1999, further promotes multicentric, economically, socially and environmentally coordinated regional development through an integrated space policy [6,8,9]. With the development of economic globalization and sustainable development strategies, the emergence of "fuzzy space" and "space flow'" has increased the complexity and uncertainty of spatial planning, and traditional strategic planning has gradually begun to spread to all scales [10].

At the same time, according to the 2005 report of the Millennium Ecosystem Assessment Plan and the Global and Regional Marine Environment Assessment Report, there is a deteriorating trend in the global coastal marine ecosystem affected by human activities [11]. Due to the high concentration of population and activities, the marine area faces great pressure, which has led to two kinds of main conflicts: first, the conflicts among human beings competing for the jurisdiction of marine space and the right to development; second, the conflicts of the increasing demand of humans being forced to further explore marine space and the decrease in marine biodiversity [12,13]. These conflicts may come from the time–space overlap of human activities at the sea or the externalities of positive and negative environments [14]. These conflicts reduce the biodiversity and robustness of marine areas, which will eventually affect the safety of human beings [15]. The conflict between the increase in human demand for developing marine space and the decrease in marine biodiversity has changed the sea through direct and indirect means in the development of the sea, challenging the existing institutional governance arrangements [16]. Therefore, marine-developed countries such as Europe and the United States have gradually formed the concept of marine space planning based on ecosystems and promoted the realization of integrated marine management based on ecosystems. Based on the theory and practical experience of urban and land spatial planning, the concept of spatial planning is applied to marine management. After continuous exploration, the concept of marine spatial planning is born. The world's marine spatial planning system has also been continuously optimized with the theoretical research, policy formulation and work practice of many experts, scholars and practitioners. To date, it has developed into a system that spans countries and focuses on marine spatial planning.

2.2. Comparison of European Countries' Marine Spatial Planning and China's Marine Functional Zoning

Foreign research on marine spatial planning started relatively early. After the introduction of the *Convention on the Law of the Sea*, the important role of marine spatial planning in marine development and protection has gradually been realized [17]. Approximately half of global marine spatial planning is formulated in the European Union [18]. The introduction of *Agenda 21* in 1992 prompted the EU to rethink the management of the oceans and seas and put forwards corresponding suggestions and initiatives; from 2002 to 2007, *Integrated Coastal Zone Management Proposals*, *Future-oriented EU Ocean Policy: European Ocean Vision* and *Blue Book on Integrated Ocean Policy* were issued, further clarifying the macro guidance role of ocean space planning [19–22]. In 2014, Directive 2014/89/EU of the European Parliament and the Council (EP&C) was enacted and established a common framework for marine spatial planning (MSP), targeting sustainable development of marine economies and sea areas; as well as the sustainable utilization of marine resources, it has been the main policy instrument in Europe [13]. Overall, EU marine spatial planning is gradually shifting from a single environmental control tool to a multipurpose marine space governance tool with blue growth as the core.

In the past 20 years, EU countries have also carried out their own practice of sea area spatial planning and have achieved remarkable results. They preliminarily completed sea area utilization planning and zoning within their territorial waters and formed a complex multilevel and multiscale "local-regional-national-international" planning and management system of. Britain is a traditional maritime power, and over the last decade it has been working to optimize and improve its marine management. Based on the land-use planning system and marine characteristics, Tyldesley proposed a framework concept for the UK marine spatial planning system, forming a marine spatial planning system that includes four levels: the United Kingdom, National, Regional and Local [23]. Based on the study of this framework concept, the United Kingdom has gradually carried out practical work on marine spatial planning and system construction. The implementation of the British Coastal Zones and Ocean Access Act in 2009 reversed the fragmentation of ocean management and clarified the management authority of British maritime areas (territorial waters, exclusive economic zones and continental shelf) to provide an institutional basis for the establishment of a marine spatial planning system. In 2011, the UK issued the *UK Marine Policy Statement*, proposing the need to establish a marine planning system and clarifying the principles, contents and policies of marine (space) planning [24–26]. According to the plan, the UK will complete the marine spatial planning of all jurisdictions by 2021. The Master Plan was established in 2003 by Belgium, which was one of the earliest countries to carry out a multipurpose sea area planning system in its territorial waters (TS) and exclusive economic zone (EEZ) [27]. The Netherlands established the North Sea 2015 Integrated Marine Management Plan for the effective use of marine resources, and marine space management is the key means of the plan [28]. In July 2004, Germany extended federal spatial planning acts to the EEZ, established a general framework for marine spatial planning in the EEZ, and completed a draft marine spatial plan for the North Sea and Baltic Sea and related environmental reports in 2005 [29].

Compared with foreign experience in marine spatial planning, the basic objectives and guiding ideology of marine spatial planning measures or plans adopted in the use and management of sea area abroad are similar to those of China's marine functional zoning [30]. The main objectives of marine spatial planning and functional zoning emphasize guiding the rational development and utilization of the sea and protecting the marine environment. Marine functional zoning divides the sea into functional zones with different types of use and different environmental quality requirements according to the geographical location of the sea, the natural environment and resources, the development and utilization and protection of the current situation and economic and social development needs [31]. Since China carried out investigation and research in the 1980s, three rounds of marine functional zoning have been prepared and implemented, and a complete planning system has been established. On the basis of marine functional zoning, the former State Oceanic Administration formulated normative documents such as *Regulations on the Management of Marine Functional Zoning* and implemented a series of management systems such as approval and paid use of sea area. At the same time, compared with foreign marine spatial planning, China's marine functional zoning has a higher legal status and a comprehensive range of implementation. The *Law of the People's Republic of China on the Administration of Sea Use* stipulates that the state implements a system of marine functional zoning, and the use of sea area must comply with marine functional zoning. The *Law of the People's Republic of China on Marine Environmental Protection* takes marine functional zoning as the basis for supervision and management of the marine environment. The *Law of the People's Republic of China on the Protection of Sea Islands* takes marine functional zoning as the basis for the preparation of island protection planning. The State Council, in its approval of the *National Marine Functional Zoning (2011–2020)*, emphasizes that marine functional zoning is the legal basis for rational development and utilization of marine resources and effective protection of the marine ecological environment and must be strictly implemented [32,33]. In summary, both marine spatial planning and marine functional zoning play an important role in strengthening the management of sea area use, coordinating the contradiction of sea use and protecting the marine ecological environment.

2.3. Evaluation Mechanism for Spatial Planning Implementation

Foreign spatial planning has a long history of development and a mature system, which has formed a systematic evaluation mechanism for planning implementation, mainly with two basic evaluation concepts of "conformance" and "performance" [34]. The concept of "conformance" focuses more on the effect of planning implementation, and there are two main methods of evaluation: one is to take the planning blueprint as the ultimate goal, compare the results of planning implementation with the blueprint, and analyze the effectiveness of planning implementation; the other is to start from the planning goals, and study the implementation of central and local planning goals in specific areas [35–38]. The concept of "performance" focuses more on the implementation process of the plan, and believes that the result of the plan is not entirely consistent with the blueprint of the plan, but more crucial is the role of the plan itself in guiding the decision-making process of regional development, including three aspects: first, the government's decisions are mainly made with reference to the plan; second, although some of the government's decisions are not in line with the content of the plan, they are made after careful consideration based on the plan and are consistent with the intent of the plan; third, the rapid development of the region makes it difficult to meet the actual needs of the plan, and the government's decisions are first revised in the plan [39,40].

The implementation evaluation of spatial planning in China mainly focuses on land use planning and urban planning but rarely involves marine area planning. The research focuses on evaluating the results, benefits and impacts of the implementation of planning. The research method is to establish a system of indicators for evaluating the implementation of the plan and to determine the weights of the indicators by using the Delphi method or hierarchical analysis to comprehensively evaluate the specific situation and problems of the implementation of the plan and then make recommendations for the revision of the plan. The assessment concept is mainly based on the assessment of planning implementation results. Although the importance of the assessment of the planning implementation process has been noted, less research has been conducted due to uncertainty and difficulty of operation, and the existing assessment of the planning implementation process focuses on the analysis of the formulation of planning implementation policies and institutional construction, as well as a brief qualitative analysis of the influencing factors of planning implementation [41,42].

3. Construction of the Evaluation Method for Marine Functional Zoning

Implementation evaluation is one of the basic links in marine functional zoning management, and its implementation is conducive to promoting marine functional zoning to give full play to its function of optimizing marine resources and guiding the marine economy. The implementation evaluation of marine functional zoning is mainly based on the concept of consistency, with the result evaluation as the main criterion and the planning blueprint or planning objective as the evaluation criterion. This paper discusses the implementation evaluation method of marine functional zoning based on blueprints (Figure 1).

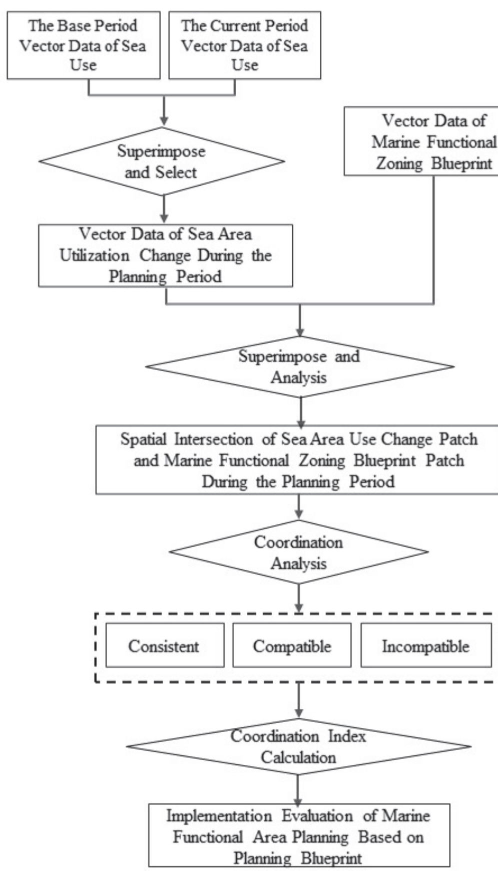


Figure 1. Implementation evaluation of marine functional zoning based on planning blueprints.

First, geographic information system (GIS) software was used to superimpose the vector data of sea use between the base period and the current period, and then we removed the patches that did not change in the type of sea use from the base period to the current period to obtain the data of patches that changed in sea use during the planning period. Second, the spatial relationship between the change in the patch of sea area and the patch of marine function division was obtained using GIS software, including "coincidence", "intersection", "inclusion", "adjacency" and "separation" [43]. "Coincidence" means that the shape, size and spatial position of the two planar patches are completely consistent. "Intersection" refers to two planar patches that do not coincide but overlap in space. "Contained" means that one facet plaque is completely inside another; "Adjacency" means that two planar patches have a common boundary and do not intersect internally. "Dissociation" means that the intersection of two planar plaques is an empty set. Third, the coordination between the patch with an "intersecting" or "containing" relationship and the patch with marine functional zoning is judged; that is, the degree to which the indicators of a patch's use activity meet the function and control requirements stipulated by marine functional zoning. The complexity of marine resources determines the multifunctionality of the sea area, which in turn leads to the existence of one or more compatible functions in the same sea area, such as the establishment of small fishing docks in aquaculture areas to facilitate the transportation of raw materials and aquaculture products [44].

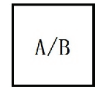
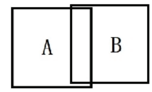
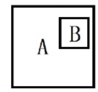
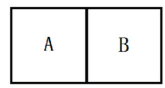
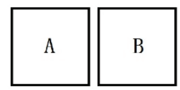
The main considerations of coordination discrimination are whether the marine utilization activities conform to the use control of marine functional zoning, whether they serve the dominant function of the zoning, whether they cause irreversible changes to the basic function of the zoning and whether the environmental protection requirements and environmental quality standards of the zoning are implemented [45]. Therefore, coordination can be divided into "consistent, compatible and uncoordinated" types. "Consistent" means that the sea area utilization type is similar to the zoning type, and all indicators fully meet the zoning use control and environmental protection requirements. "Compatible" means that although the sea area utilization type is not consistent with the zoning type, it can serve the formation of the dominant function of the functional zoning and meet the environmental quality standards of the functional zoning, for example, the construction of small tourist docks in the tourism and entertainment area; "Uncoordinated" means that the type of sea area utilization will cause irreversible changes to the basic functions of the zoning function zoning, or the environmental quality standard of sea area utilization does not meet the control requirements of the zoning function. For example, the construction of ports will change the natural background and water environment of the sea area, so it cannot be carried out in the aquaculture area or the breeding area.

Finally, the coordination index of marine functional zoning implementation is calculated according to the coordination between the current patch and the planned patch, and the implementation effect of marine functional zoning is judged comprehensively.

3.1. Spatial Relationship between Sea Area Use Change Patches and Blueprint Patches

The spatial relationship between the patch of sea area use change and the patch of blueprint includes five types: "overlap", "intersection", "inclusion", "adjacency" and "separation" (Table 1). The spatial relationship definition is mainly completed by using the spatial overlay tool in ArcGIS10.2 software. If the shape, size and space position of the two are exactly the same after superposition, it is "coincidence". If the two planar patches do not coincide but overlap in space, it is "intersecting"; if a facial-shaped patch is completely inside another facial-shaped patch, it is "contained"; if two planar patches have a common boundary and do not intersect internally, it is "adjacent". If the intersection of two planar plaques is an empty set, it is referred to as "phase separation".

Table 1. Spatial relationship types of sea area use change patches and planning blueprint patches.

Spatial Relationship Type	Meaning	Sketch
Overlap	Patch A and patch B completely coincide	
Intersection	Patch A partially overlaps with patch B	
Inclusion	Patch B is inside patch A	
Adjacency	Patch A and patch B have a common boundary and no overlap inside	
Separation	The intersection of patch A and patch B is empty	

3.2. Coordination between Sea Area Use Change Patches and Planning Blueprint Patches

Coordination discrimination mainly includes the discrimination of conformity of sea area use, the discrimination of conformity of sea area environmental quality standard and the discrimination of the influence of sea area utilization. In terms of the discrimination steps, the first criterion should be the conformity of sea use, that is, whether the use type is consistent or similar to the functional zoning type; if not, the coordination is "consistent"; if not, the next criterion should be carried out. The second step is to judge whether the environmental quality standard of the sea area utilization type meets the environmental protection control requirements of functional zoning. If so, the third step is to judge whether the coordination is "uncoordinated". The third step is to determine whether the sea area utilization type will cause irreversible changes to the basic functions of zoning function zoning. If so, the coordination is "uncoordinated"; if not, the coordination is "compatible".

3.3. Coordination Index of Marine Function Regionalization

According to the coordination index, the implementation effect of marine function zoning is comprehensively judged, and the calculation is shown in Formula (1), where W is the coordination index, N represents the spatial relationship of patches, where the values of "overlap", "intersection" and "inclusion" are 1 and the values of "adjacency" and "separation" are 0. S1, S2 and S3 are patch areas with "consistent", "compatible" and "incompatible" coordination, respectively. S4 is the total area of sea use change patches; A reflects the level of conflict between sea area utilization type and zoning blueprint, among which the impact of development and utilization of marine reserves is the most serious, which is set as 0.00; the influence of the fishery sea being developed into construction sea (such as industrial sea) or construction sea being developed into fishery sea is the next, with 0.25.

$$W = N \times (S\_1 \times 1.00 + S\_2 \times 0.50 + S\_3 \times A)/S\_4 \quad (1)$$

Figure 2 shows the implementation evaluation logic of marine functional zoning based on the planning blueprint. First, the blueprint data of marine functional zoning and the change data of sea area utilization are overlapped in space. Activity of Marine functional areas—A Marine use C, Marine functional areas using active D, Marine functional areas, Marine B—Marine use C, Marine functional areas, Marine use D superposition of four kinds of results, analysis and coordination and calculated Marine functional zoning index W, coordination of the Marine functional zoning implementation effect assessment (Table 2).

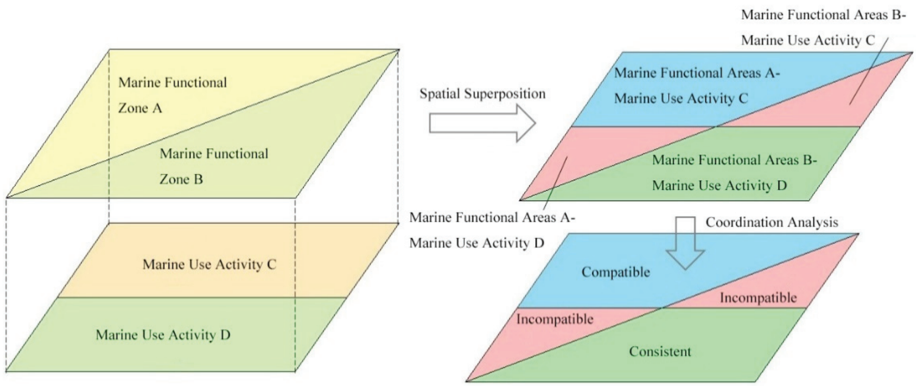


Figure 2. An example of implementation evaluation of marine functional zoning based on planning blueprints.

Table 2. Evaluation criteria for the implementation effect of marine functional zoning.

Index of Coordination of Marine Functional Zoning (W)	Implementation Effect of Marine Functional Zoning
W = 1	Completely consistent
$0.8 \leq W < 1$	Preferably
$0.6 \leq W < 0.8$	Commonly
$0.4 \leq W < 0.6$	Poor
$W < 0.4$	Range

4. Implementation Evaluation of Marine Functional Zoning of Wenzhou City (2013–2020) Based on the Planning Blueprint

4.1. Marine Functional Zoning of Wenzhou City (2013–2020) Blueprint for Functional Zoning

Marine Functional Zoning of Wenzhou City (2013–2020) was implemented in 2013 to coordinate and regulate various types of marine activities in Wenzhou, strengthen the protection of marine resources and the environment, promote the construction of marine economic development demonstration zones and serve as the basis for the city's marine development and utilization, management and protection. *Marine Functional Zoning of Wenzhou (2013–2020)*, which refers to *Technical Requirements for the Preparation of Provincial Marine Functional Zoning* and *Technical Requirements for the Preparation of Municipal and County-level Marine Functional Zoning in Zhejiang Province*, divides the Wenzhou sea area into eight first-class functional zones, including an agriculture and fishery zone, a port and shipping zone, an industry and urban sea zone, a tourism and recreation zone, a marine protection zone, a special use zone, a mineral and energy zone, and a reserved zone, and 23 second-class functional zones under them. According to the vector data provided by the Wenzhou Bureau of Natural Resources and Planning, the blueprint structure of 2020 Wenzhou marine functional zones estimated in *Wenzhou Marine Functional Zoning (2013–2020)* is shown in Table 3, in which the area of agriculture and fishery zones is the largest, accounting for 75.04%, which is because most of the sea area that are not suitable for development and construction and have no outstanding ecological and environmental protection value are delimited as fishing zones. The area of reserved zones is the second, accounting for 13.65%, which is mainly located in the periphery of the marine-protected zones and exists as a buffer zone of the marine protected zones. The area of port shipping zones is next, accounting for 5.81%, mainly including Yueqing, Dongtou, Oujiang Estuary, Feiyun River, Aojiang Estuary, Pacao, Xiaguan and seven other port zones, seven channel zones and eight anchor zones. Marine-protected zones accounted for 3.01% of the area, including Ximen Island, east of Dongtou Islands, Nance Island, Wenzhou Shupaisha Island, Nanji Islands, North and South Pan Mountain, Tongpan Island, and Qixing Island. Industrial and urban sea zones, tourism and recreation zones, mineral and energy areas, and special use zones accounted for 2.49% of the total area (Figure 3).

Table 3. The structure of functional zones in *Wenzhou Marine Functional Zoning (2013–2020)*.

Functional Zone Type	Proportion of Functional Zones/%	Proportion of the Number of Map Spots in Functional Zones/%
Agricultural and fishery zone	75.04	25.93
Reserved zone	13.65	18.52
Port and shipping zone	5.81	16.67
Marine-protected zone	3.01	14.81
Industrial and urban sea zone	1.82	12.96
Tourism and recreation zone	0.58	5.56
Special use zone	0.08	3.70
Minerals and energy zone	0.01	1.85
Total	100.00	100.00

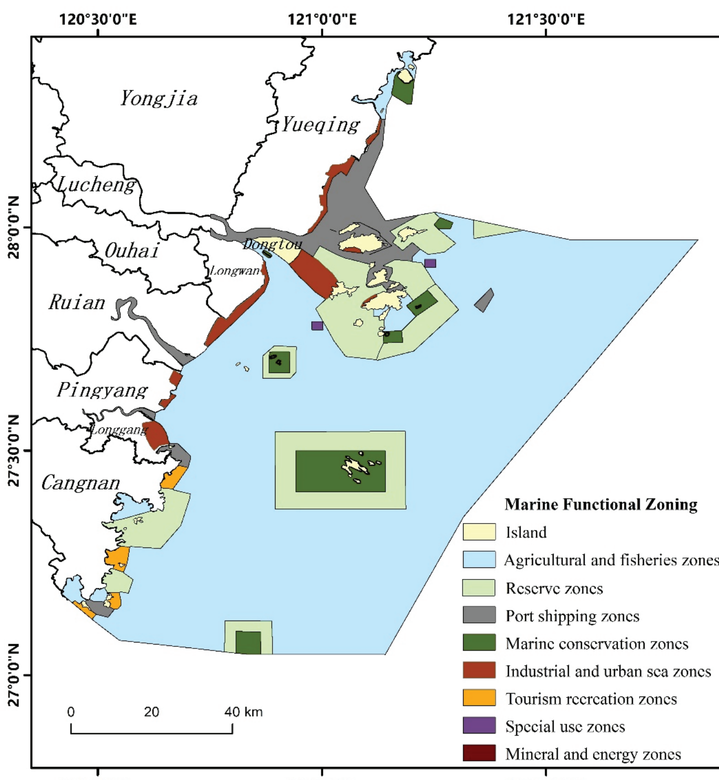


Figure 3. Blue print of functional zones of Wenzhou Marine Functional Zoning (2013–2020).

4.2. Sea Area Utilization of Wenzhou City from 2013 to 2020

According to the standard of *Sea Area Use Classification (HYT 123-2009)*, the sea area use data types of Wenzhou are divided into eight first-class sea areas for fishery, industry, tourism and entertainment, transportation, land engineering, special use, undersea engineering and other uses, and 18 second-class areas. The vector data of 2013 and 2020 sea area utilization from the dynamic management system of sea area utilization in Wenzhou were imported into ArcGIS10.2 software, and the patches with no change in sea area utilization type were eliminated. After that, the spatial vector attributes of various sea area utilization and map spots in Wenzhou from 2013 to 2020 could be obtained statistically (Table 4). From 2013 to 2020, sea area utilization structure of Wenzhou was mainly composed of fishery seas (25.63%), industrial seas (21.81%) and transportation seas (35.52%). Among them, the sea used for fisheries is mainly used for aquaculture and open aquaculture. The sea used for aquaculture is mainly distributed in Yongxing Street, Haibin Street, Xinghai Street and Haixi Town of Pingyang County in the Longwan District, and a small amount is distributed in Beiao Street of Dongtou Island and the coast of Gate Town of Gate Island. Open aquaculture seas are mainly distributed in Xinghai Street, Yongxing Street and other mainland coastal areas of the Longwan District, and small amounts are found in Nanji town of Nanji Island, Luxi township of Luxi Island, Ximen Island (Yandang town) and Daqu village of Daqu Island. The industrial sea is mainly used for the electric power industry and is mainly distributed in Yanting town of Longgang city, Nanyue town of Yueqing city and other continental coastal areas. Transportation by sea includes a port with sea and road and a bridge with sea, a port with sea distribution in oujiang, Feiyun River, Aojiang and Zhuangyuan Ao Island, Xiaoming Island, Gate Island and other island coast and Yueqing City Of Nanyue town and Puqi town; road and bridge sea for the Yongdong–Dongguan highway cross-sea sections, distribution in the Oujiang mouth, Feiyun river mouth, Aojiang mouth and Dayuwan, Wenzhou City internal cross-sea, a cross-river bridge, such as Oujiang mouth rail transit S1 line, Ni Yu Island and the Dongtou gorge on the S77 provincial road extension line Longwan to the Dongtou Shugang highway project (Figure 4).

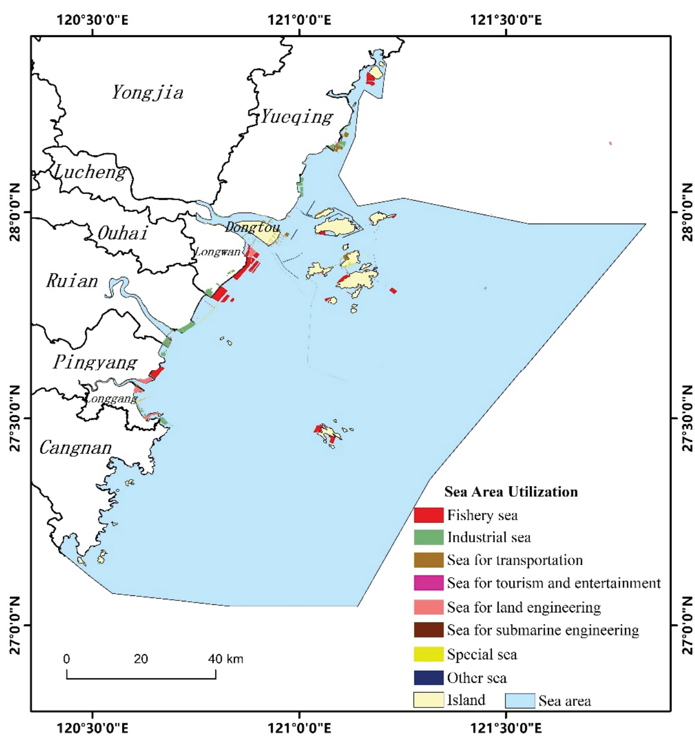


Figure 4. Sea area utilization in Wenzhou from 2013 to 2020.

Table 4. The utilization structure of sea area in Wenzhou from 2013 to 2020.

Type of Sea Area	Percentage of Sea Parcel Number/%	Percentage of Sea Parcel Area/%
Fishing in the sea	18.33	25.63
Industrial use sea	21.00	21.81
Sea for transportation	45.33	35.52
Sea for land engineering	3.83	6.60
Special sea	4.83	6.12
Other sea	1.83	2.74
Sea for submarine engineering	3.50	1.39
Sea for tourism and entertainment	1.33	0.19
Total	100.00	100.00

5. Discussion

The marine functional zoning of Wenzhou city (2013–2020) was compiled according to the classification system of Technical Requirements for Marine Functional Zoning at the provincial level and Technical Requirements for Municipal and County-level Marine Function Zoning at the Zhejiang Province, while the sea area utilization data from 2013 to 2020 were compiled according to the standard of *Sea Area Use Classification (HYT 123-2009)*. Therefore, it is necessary to distinguish the coordination between the two classification systems. It should be pointed out that the blueprint of Wenzhou City Marine Functional Zoning (2013–2020) does not subdivide the industrial and urban construction areas and tourism, leisure and entertainment areas into the second class, so the discrimination process is not differentiated. In ArcGIS10.2, the marine utilization data from 2013 to 2020 and vectorized blueprint data of 2020 are analyzed for spatial superposition and coordination, and the coordination index of marine functional zoning is calculated to be 0.81, indicating that the implementation effect of *Wenzhou Marine Functional Zoning (2013–2020)* is good. The proportions of plaque areas with "consistent", "compatible" and "incompatible" characteristics were 69.42, 14.87 and 15.71%, respectively. The patch area of the "compatible" type accounted for 14.87%, mainly including mixed utilization between ports, urban construction, fishery infrastructure and stratified mixed utilization between waterways, undersea tunnels, roads and bridges, indicating that Wenzhou's marine economy has achieved some results in the mixed utilization and stratified three-dimensional utilization of sea areas. However, the level of mixed utilization and three-dimensional utilization is still low (Figure 5).

The concept of consistency can accurately determine the deviation between the initial planning and the implementation results and then provide a basis for the revision and rearrangement of the planning, which is the most widely used logical thinking in China's existing planning evaluation practice [46,47]. Due to the complexity and continuity of marine systems and the limited monitoring data of marine areas, the implementation evaluation of marine functional zoning should be based on the concept of consistency and adopt the blueprint or target as the evaluation reference standard. Based on the concept of consistency and the marine functional zoning blueprint, this paper discriminates the coordination between marine use and the marine functional zoning blueprint from three aspects: conformity of marine use, conformity of environmental quality standards, and influence of development and utilization, and calculates the coordination index of marine functional zoning to construct the implementation evaluation method of marine functional zoning. The method has two advantages: first, it is easy to obtain data, and the evaluation only needs the vector data of the current situation of marine utilization and the vector data of the blueprint of marine functional zoning. The collection and maintenance of such data is one of the basic tasks of the local marine management departments. Second, it is easy to operate. This method can be realized with the help of common geographic information system software (such as ArcGIS). The operation steps are simple and easy to get started. Therefore, this method has strong scientific applicability, operability and extensibility and can provide a reference for the implementation and evaluation of marine functional zoning in various areas. At the same time, this method also found some disadvantages in the empirical process. In the process of judging the coordination between marine area utilization change patches and planning blueprint patches, the main way to judge the impact of sea area utilization is expert scoring, which is subjective and may affect the accuracy and objectivity of the evaluation results. After that, in the process of research and demonstration, it is necessary to establish an objective and efficient evaluation system. AHP, a matter-element model and other methods can be used for multi-factor evaluation and standard grading, and socio-economic data can be used instead of experts' scoring so as to improve the objectivity of the evaluation system.

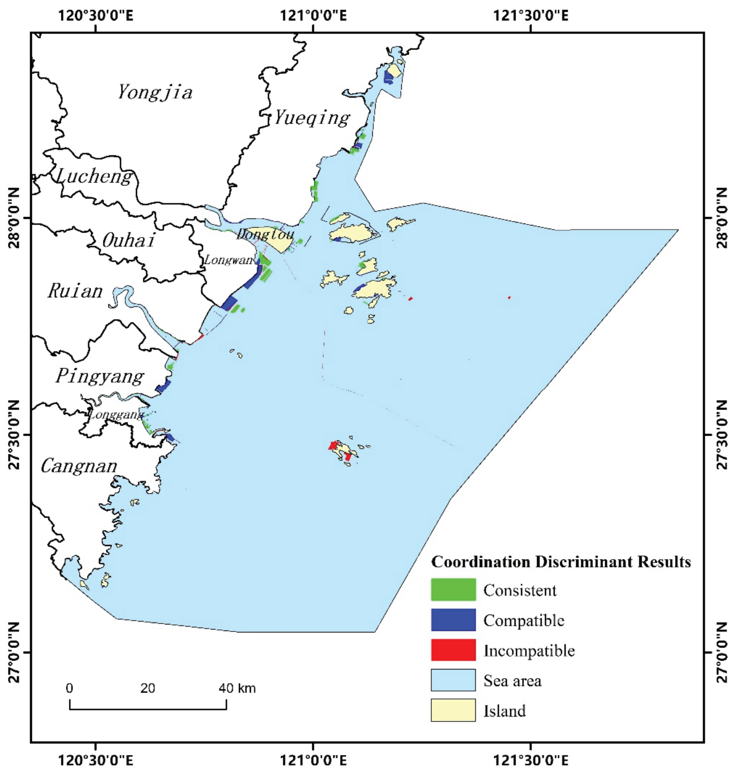


Figure 5. Coordination analysis between sea area utilization in Wenzhou from 2013 to 2020 and Wenzhou Marine Functional Zoning (2013–2020).

In addition, the construction of a marine functional zoning implementation evaluation method is of great significance to the compilation and implementation evaluation of the marine part of territorial space planning. On the one hand, marine functional zoning and other similar spatial planning evaluations are the basis and foundation of the compilation of the marine part of territorial spatial planning. The Ministry of Natural Resources has issued a number of documents emphasizing the importance of marine functional zoning, urban overall planning, land use overall planning and other spatial planning implementation evaluations and regard it as one of the basic tasks of the new round of territorial space planning. On the other hand, the implementation evaluation method of marine functional zoning can provide a reference for the planning evaluation of the sea-related part of territorial spatial planning. In the existing marine planning implementation of planning standards and Wenzhou and other places, including all kinds of functional zoning, planning blueprints are still the main expression forms of the achievements of national spatial planning at all levels. Thus, as proposed in this paper, based on the concept of consistency and planning, the blueprint of planning implementation evaluation methods can be used as a future reference for the implementation of the national spatial planning evaluation logic, adjusting the evaluation standard, index parameters, etc.

6. Conclusions

Marine functional zoning is an important tool for governments at all levels to implement marine spatial governance, which is based on the carrying capacity and utilization suitability of marine ecosystem to allocate human activities for sea use, so as to realize the sustainability of the marine economy and the ecological environment. Based on the concept of consistency, this paper innovatively proposes the logic of judging the coordination between the current situation of sea area utilization and the blueprint of marine functional zoning and the integrated calculation method of the coordination index of marine functional zoning, taking Wenzhou as an example. The research shows that the coordination index between the sea area utilization in Wenzhou from 2013 to 2020 and the blueprint of the functional area in 2020 estimated by Wenzhou Marine Functional Zoning (2013–2020) is 0.81, which shows that the implementation effect of Wenzhou marine functional zoning is good. The patch area of "incompatible" type accounts for 15.71%. The main conflict types of farming and animal husbandry areas are developed into industrial sea, tourism and entertainment sea, and marine-protected areas are developed and utilized. The patch area of "compatible" type accounts for 14.87%, which mainly includes the mixed utilization among ports, industry, urban construction and fishery infrastructure, and the layered mixed utilization among waterways, undersea tunnels, roads and bridges, indicating that Wenzhou's marine economy has made great progress in the mixed utilization and layered three-dimensional utilization of sea areas.

According to the evaluation results of coordination of marine functional zoning in Wenzhou, this paper puts forward the following three suggestions: (1) Adhere to the principle of ecological priority, strengthen the protection and construction of marine ecological environment in Wenzhou, improve the quality of marine environment and ensure regional environmental security. At the same time, adhere to the principle of marine ecological optimization and coordinated development of regional economy, change the mode of economic growth and support social and economic sustainable development with sustainable utilization of environment and resources. (2) Targeted measures should be taken in areas with serious ecological damage in the sea area, and the principle of ecological priority should be adhered to while ensuring the interests of the masses, combining prevention and control. Reduce the intensity of sea area use for uncoordinated conflicting sea areas and ban illegal sea-use projects. The existing marine environmental risk control and emergency capacity building is very weak, and there are obvious shortcomings in marine environmental law enforcement team, supervision ability and management means; in particular, the environmental supervision ability of coastal aquaculture and coastal engineering needs to be strengthened. (3) Fully consider the impact of land-based watershed and regional environmental pollution on the marine ecological environment, and strictly control the discharge of land-based pollutants to the ocean. At the same time, we should actively implement the combination of prevention and control to prevent the occurrence of marine pollution incidents and other incidents that damage the marine ecological environment.

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Article

Spatial and Temporal Changes of Landscape Patterns and Their Effects on Ecosystem Services in the Huaihe River Basin, China

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Abstract: Landscape pattern changes caused by human activities are among the most important driving factors affecting ecosystem spatial structure and components, and significantly impact ecosystem services. Understanding the relationship between landscape patterns and ecosystem services is important for improving regional conservation and establishing ecosystem management strategies. Taking the Huaihe River Basin as an example, this study used land-use data, meteorological data, and topographic data to analyze the spatial and temporal changes in landscape patterns via landscape transfer matrix and landscape indices, and measured four ecosystem services (water retention, soil retention, carbon storage, and biodiversity conservation) with the InVEST models. Furthermore, correlation analysis and global spatial autocorrelation coefficient were used to analyze the impact of landscape pattern changes on ecosystem services. The results showed grassland and farmland areas had continuously decreased, while built-up land and affected water had significantly increased. Landscape fragmentation was reduced, the connectivity between patches was weakened, landscape heterogeneity, evenness, and patch irregularity were increased. Changes in landscape composition and configuration have affected the ecosystem services of the Huaihe River Basin. The reduction in grassland areas and the increase in built-up land areas have significantly reduced the capacity for soil retention, carbon storage, and biodiversity conservation. Spatially, regions with low landscape fragmentation and high patch connectivity had a higher water retention capacity and biodiversity conservation, while soil retention and carbon storage were opposite. Temporally, reduction of landscape fragmentation and increase of patch shape irregularity had a negative effect on water retention, carbon storage, and biodiversity conservation, while soil retention was not sensitive to these changes. The findings in this paper promote an understanding of the relationship between landscape patterns and ecosystem services on a large scale and provide theoretical guidance for ecosystem management and protection planning in the Huaihe River Basin, China.

Keywords: landscape pattern; ecosystem services; InVEST models; global bivariate spatial correlation; Huaihe River Basin

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1. Introduction

Landscape pattern refers to the landscape's structural composition (type and proportion) and spatial configuration (patch size and spatial distribution), which can be greatly influenced by human activities and climatic factors [1–3]. At a regional scale, landscape pattern changes have led to a series of ecological problems and directly affected energy flow, hydrological cycles, primary productivity, species diversity, and so on [4–7]. They have been widely recognized as one of the most important driving forces of ecosystem service processes [8–10]. Previous studies have shown that landscape structural composition changes directly impact ecosystem services [11,12]. The increasing scale of conversion from natural and semi-natural landscape to built-up land and farmland results in a considerable decline in ecosystem services [13,14]. Moreover, landscape spatial configuration changes affect ecosystem services processes and the trade-offs between services [15–17].

Ecosystem services provide life-supporting goods and services, are directly or indirectly obtained from the process and function of natural ecosystems that are vital to human survival and development [18–20], and are a bridge between natural ecosystems and human well-being [2,8]. They can be categorized into four types: provisioning, regulating, cultural, and supporting services [21]. However, rapid urbanization and population growth have caused subsequent increases in human interference, which have profoundly altered landscape patterns [22–24], and these problems have greatly damaged the service functions of ecosystems [25–28]. The Millennium Ecosystem Assessment reported that global ecosystem services are declining at an unprecedented rate [21]. In this context, understanding the driving mechanism of ecosystem services is urgently needed to maintain their sustainable development [2,29,30].

Numerous studies have quantified the impacts of landscape pattern changes on ecosystem services to understand the interactions between landscapes and ecosystem services [31–34]. However, few studies have explored this phenomenon over long periods and in large geographic areas. The relationship between landscape patterns and ecosystem services depends on the spatial variability of drivers and stressors [5], and focusing on local or small catchment scales may ignore the impacts of broadscale drivers [35]. Therefore, exploring the relationship between landscape patterns and ecosystem services over larger geographic areas has important practical significance and can also provide theoretical guidance for landscape planning and ecologically sustainable development.

Rapid economic development and urbanization have led to changes in the environment [16,22,36], which has led to the reduction of the capability of ecosystem services [2,20]. The Huaihe River Basin has become an important agricultural and industrial base in China due to its suitable environment and rich natural resources [37–39]. Although huge investment has been made to improve the environment of the Huaihe River Basin, it is difficult to achieve great improvement in the short term [40–43]. In October 2018, the Chinese government released the "Huaihe River Economic Belt Development Plan" that emphasized the excellent location and important status of the Huaihe River Basin and considered accelerating the development of the Huaihe Ecological and Economic Belt which is of great significance in advancing ecological protection [44]. Therefore, the Huaihe River Basin was selected as a case study to explore the way changes in landscape patterns affect ecosystem services to meet governmental needs for scientific information and references to formulate policies that promote ecologically sustainable development and protection.

In this paper, we seek to explore the relationship between landscape patterns and ecosystem services through a case study of the Huaihe River Basin from 1990 to 2018. The objectives of this study are as follows: (1) to quantify the spatial and temporal changes of landscape patterns using a landscape transfer matrix and landscape indices, (2) to estimate the evolution of ecosystem services using InVEST models, and (3) to analyze the spatiotemporal relationship between the landscape and ecosystem services. The results will improve our understanding of the relationships between landscape patterns and ecosystem services on a broad scale, and provide theoretical guidance for ecosystem management and protection planning in the Huaihe River Basin, China.

2. Materials and Methods

2.1. Description of the Huaihe River Basin

The Huaihe River Basin is located in eastern China, between $30°55'-37°50'$ N and $111°55'-122°42'$ E (Figure 1). It covers an area of approximately 3.3×10^5 km^2 crossing Henan, Hubei, Anhui, Jiangsu, and Shandong Provinces [45]. With a dense population of 600 person/km^{2,} which is far higher than the national population density of 148 person/km^2 [37,39]. The main stream of the Huaihe River originates from Tongbaishan Mountain in Henan Province, China, and flows eastward into the Yellow Sea [46]. The topography is dominated by low hills in the western and north-eastern parts of the basin, which cover 1/3 of the total area, and by extensive plains in the remaining 2/3 [47]. The basin is located in the South-North transition zone of China, where the mean annual precipitation and temperature are 883 mm and 11−16 °C [48], which provide a suitable living environment for organisms. With the high-intensity exploitation of resources, ecological systems have been under great pressure, and ecological and environmental problems such as subsidence and degradation of arable land quality are becoming more serious [47].

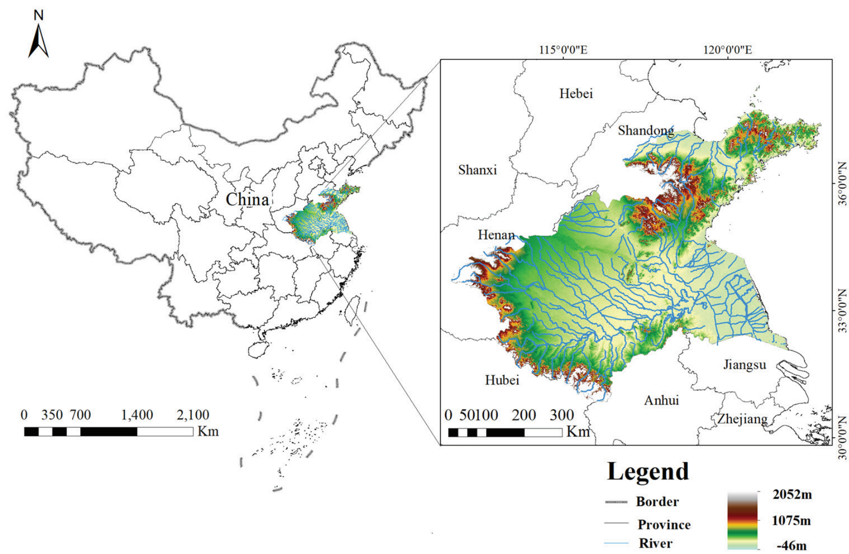


Figure 1. Location of the Huaihe River Basin.

2.2. Data Sources and Preprocessing

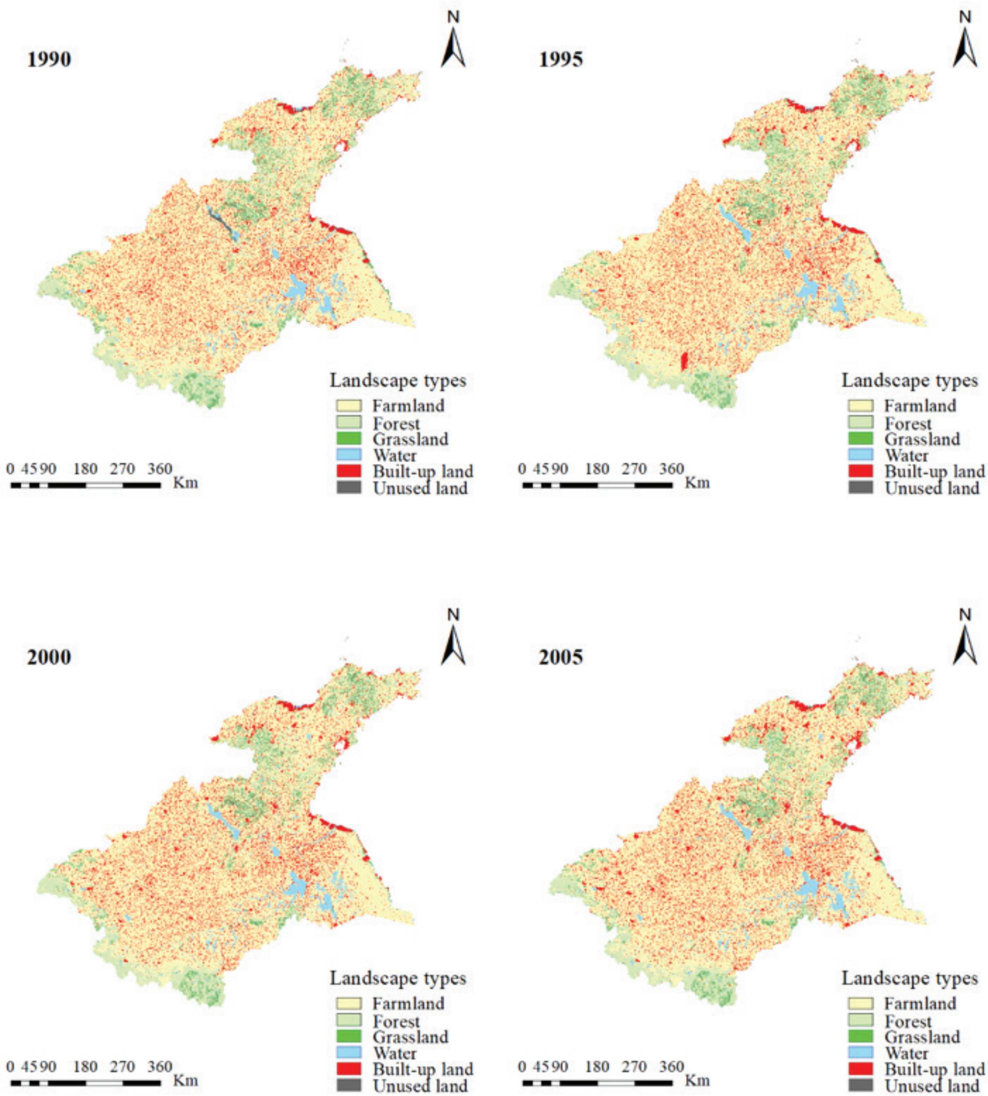
Land use data (spatial resolution of 1 km) for 1990, 1995, 2000, 2005, 2010, 2015, and 2018 were sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 11 December 2021). These Landsat remote sensing images generated a long time series land-use dataset using human visual interpretation, and the overall accuracy was greater than 90% [49]. Based on previous studies [2], we used ArcGIS software to further integrate the land use data into six landscape types: farmland, forest, grassland, water, built-up land, and unused land (Figure 2). Digital elevation model (DEM) data (spatial resolution of 1 km) was downloaded from the geospatial data cloud platform (http://www.gscloud.cn, accessed on 11 December 2021) and used to divide the watershed. Meteorological data such as temperature and precipitation, effective soil moisture, soil texture, etc., came from the National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn, accessed on 13 December 2021). The rainfall erosivity factor (R factor) with a spatial resolution of 1 km came from the Climate Change Impact Assessment (CLICIA) Group at the Beijing Normal University (https://dx.doi.org/10.12275/bnu.clicia.rainfallerosivity.CN.001, accessed on 13 December 2021).

2.3. Landscape Transfer Matrix

The landscape transfer matrix has often been used to describe the mutual transfer of landscape types [32,50] and reveal the structural characteristics of landscape patterns [51]. This study calculated the mutual transfer of landscape types in the initial and final stages to reflect the temporal changes of landscape types in the Huaihe River Basin. The formula is written as:

$$S_{ij} = \begin{bmatrix} S_{11}\, S_{12} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1}\, S_{n2} & \cdots & S_{nn} \end{bmatrix} \tag{1}$$

where S_{ij} is the change in area from i to j; n is the number of landscape types; and i and j are the landscape types at the beginning and end of the study period, respectively.



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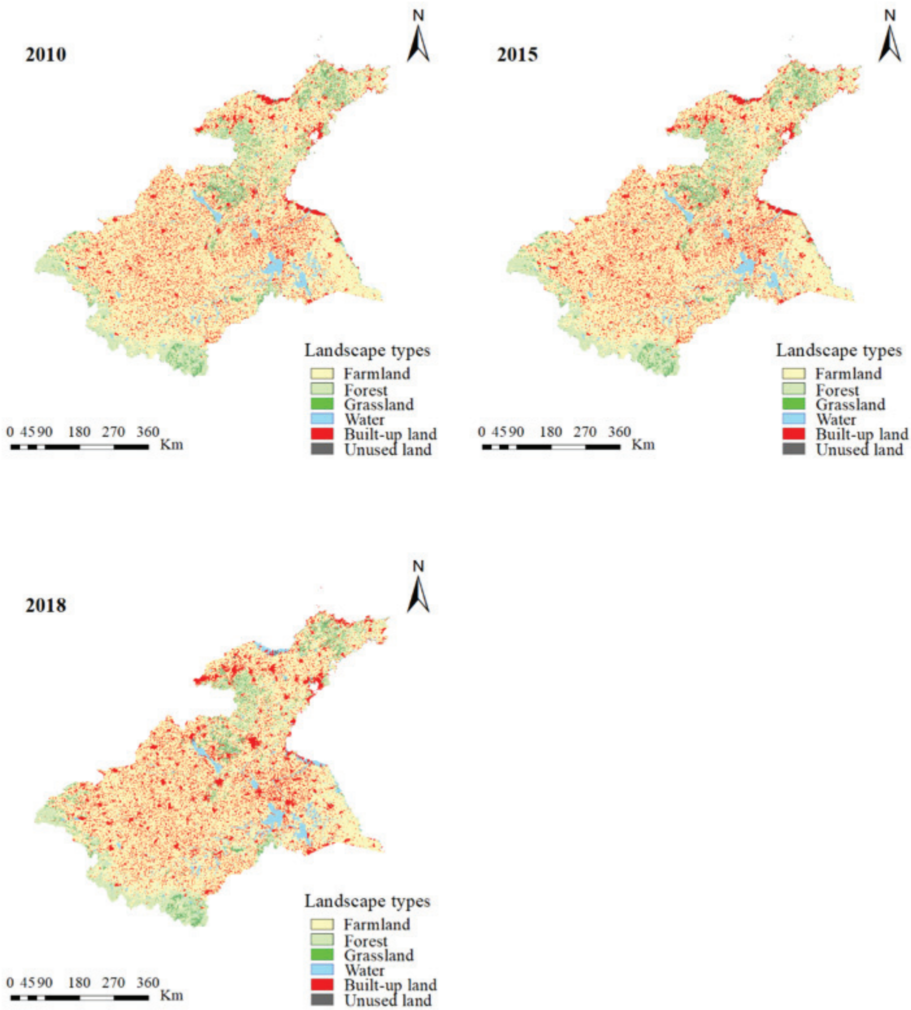

Figure 2. Spatial distribution of landscape types in Huaihe River Basin from 1990 to 2018.

2.4. Calculation of Landscape Indices

Landscape indices are widely used to reflect landscape spatial configurations [3,4] and study landscape pattern changes [52]. Based on previous studies and the landscape structural characteristics in the Huaihe River Basin, and to avoid redundancy between landscape indices, conducted a multicollinearity test using SPSS 22 software [16], five landscape indices were chosen to quantify landscape pattern characteristics at the landscape level, including Mean Patch Area (AREA_MN), Mean Fractal Dimension Index (FRAC_MN), Shannon's Diversity Index (SHDI), Aggregation Index (AI) and Contagion Index (CONTAG). Overall landscape indices and those in every sampling grid using a moving window were calculated using Fragstats 4.2 software. The ecological implications and mathematical expressions for each landscape index are as follows:

(1) AREA_MN: A key index of the degree of landscape fragmentation. A smaller value represents a higher degree of fragmentation.

$$\text{AREA\_MN} = \frac{A}{N} \quad (2)$$

where A is the total area of patches; and N is the number of patches.

(2) FRAC_MN: An expression of patch shape complexity. The closer the expression is to 1, the simpler and more regular the patch shape is.

$$\mathrm{FRAC\_MN} = \frac{\sum_{i=j}^{m} \sum_{j=1}^{n} \frac{2\ln(0.25pij)}{\ln(Aij)}}{ni} \tag{3}$$

where p_{ij} is the perimeter (m) of patch ij; A_{ij} is the area (m^2) of patch ij; n_i is the number of patches in the landscape of each patch type i; and $1 \leq \mathrm{FRAC\_MN} \leq 2$.

(3) SHDI: Describes the diversity and complexity of landscape patches. This value increases as the number of different patch types increases and/or the proportional distribution of area between patch types become more equitable.

$$\mathrm{SHDI} = -\sum_{i=1}^{m} (P_i \times \ln P_i) \tag{4}$$

where P_i is the proportion of the landscape occupied by patch type i, m is the number of patch types in the present landscape, and $\mathrm{SHDI} \geq 0$, without limit.

(4) AI: Indicates the degree of aggregation and non-randomness. The smaller the index value, the greater the dispersion of different types of patches in the landscape.

$$\mathrm{AI} = 100 \times \left[\sum_{i=1}^{m} \left(\frac{g_{ii}}{\max_{g_{ii}}} \right) \times P_i \right] \tag{5}$$

where g_{ii} is the number of similar adjacencies between pixels of patch type i based on the single-count method; $\max_{g_{ii}}$ is the maximum number of similar adjacencies between pixels of patch type i and is based on the single-count method; P_i is the landscape proportion comprised of patch type i; m is the number of patch types, and $0 \leq \mathrm{AI} \leq 100$.

(5) CONTAG: Indicates the degree of aggregation or extension. The larger the index value, the higher the aggregation degree, and the better the connectivity.

$$\mathrm{CONTAG} = 1 + \frac{\sum_{i=1}^{m} \sum_{k=1}^{m} \left[(P_i) \left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right) \right] \left[\ln(P_i) \left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right) \right]}{2\ln(m)} \tag{6}$$

where P_i is the area percentage of type i patches; g_{ik} is the number of adjacent patches of type i and type k; m is the number of patches types of landscape, and $0 < \mathrm{CONTAG} \leq 100$.

2.5. Calculation of Ecosystem Services

2.5.1. Ecosystem Services Selection

The topographic and climatic conditions of the Huaihe River Basin provide a wide range of essential ecosystem services to human society in the study area, including the supply of freshwater, maintaining biodiversity, soil retention, and carbon storage [53–55]. Freshwater supply and carbon storage have a direct influence on human survival [56], and biodiversity and soil retention promote and protect human well-being [8,57]. Taking into account the high-intensity resource development, agriculture, and other human activities that pose threats to the supply of ecosystem services, four ecosystem services were selected for measuring the ecosystem services capability of the Huaihe River Basin: water retention, soil retention, carbon storage, and biodiversity conservation.

2.5.2. Ecosystem Services Evaluation

There are various methods for evaluating ecosystem services capabilities, which mainly include monetary evaluation, GIS-based evaluation, and models such as InVEST, GLOBIO, and ARIES, of which monetary evaluation and InVEST models are the most commonly used [12,16,18,58–60]. However, monetary evaluation has been widely questioned and criticized since it was first proposed [61]. The InVEST models developed by the Natural Capital Project comprise nine terrestrial models and eight marine models and are capable of analyzing ecosystem service scenario predictions. They have been widely used to map ecosystem services provision and their spatial relationships, and are widely recognized as suitable for ecosystem services assessments [12,27,62–64].

InVEST (Version.3.9.2) is a GIS-based method for estimating ecosystem services across a landscape, given different land-use scenarios [65]. This study used the Water Yield model (for water retention), the Sediment Delivery Ratio model (for soil retention), the Carbon Storage and Sequestration model (for carbon storage), and the Habitat Quality model (for biodiversity conservation) to evaluate the ecosystem services in the Huaihe River Basin.

Water retention is defined as the ability of ecosystems to intercept or store water resources from precipitation, which is calculated as the amount of precipitation minus evapotranspiration and runoff [66]. Then the annual water yield for each pixel is estimated based on average annual precipitation and the Budyko curve [67].

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x \tag{7}$$

where Y_x is the water yield of pixel x (m^3); AET_x is the pixel x annual actual evaporation (mm); P_x is the annual precipitation of pixel x (mm).

Soil retention was calculated using the InVEST Sediment Delivery Ratio model as the average annual amount of soil loss from each parcel of land. The model uses the Universal Soil Loss Equation to identify a land parcel's potential soil yield and capacity to retain sediment [67].

$$rusle_x = R_x \times K_x \times LS_x \times C_x \times P_x \tag{8}$$

where R_x is rainfall erosivity($MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot a^{-1}$); K_x is soil erodibility ($t \cdot h \cdot MJ^{-1} \cdot mm^{-1}$); LS_x is a slope length-gradient factor (unitless); C_x is a cover-management factor (unitless); and P_x is a support practice factor (unitless).

Carbon storage was calculated using the InVEST Carbon Storage and Sequestration model to estimate aboveground biomass, belowground biomass, soil, and dead organic matter per landscape type [66]. We parameterized the model using biomass values from studies in the Huaihe River Basin and the Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC) [68].

$$S_{cx} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{9}$$

where S_{cx} is the amount of carbon stored in Mg in pixel x; C_{above} is the aboveground carbon value; C_{below} is the belowground carbon value; C_{soil} is the soil carbon value; C_{dead} is the dead carbon value.

Biodiversity conservation was calculated using the InVEST model for Habitat Quality, which estimates the extent of suitable habitat for organisms by combining information on landscape suitability and threats to biodiversity [67]. The relative impact of each threat and the distance between habitats and sources of threats are referred to in the published literature [4,69,70].

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^2}{D_{xj}^2 + K^2}\right) \tag{10}$$

where Q_{xj} is habitat quality, H_j is habitat suitability; D_{xj} is the total threat level in pixel x with habitat type j; K is a scaling parameter.

2.6. Analysis of the Relationships between Landscapes and Ecosystem Services

Spearman correlation analysis was used to study the relationships between temporal changes between landscape patterns and ecosystem services using SPSS 22 software [33]. The global bivariate spatial correlation represents spatial features at the entire scale through Moran's I, which was used to analyze spatial relationships between ecosystem services and landscape patterns [22]. The spatial analyses were conducted using GeoDa software (http://geodacenter.github.io/, accessed on 3 December 2021). The formula is written as:

$$I_{sr} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(\frac{yi,s-\bar{y}_s}{\sigma_s}\right)\left(\frac{yi,r-\bar{y}_r}{\sigma_r}\right)}{(n-1)\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij})} \quad (11)$$

where I_{sr} is the bivariate global autocorrelation coefficient of landscape index s and ecosystem services characterization indicator r; n is the amount of data; W_{ij} is the spatial weight between elements i and j; yi, s and yi, r are the landscape indices and ecosystem services at pixel i; σ_s and σ_r are the variances; $\bar{y}_s$ and $\bar{y}_r$ are the average values of landscape indices and ecosystem services.

3. Results

3.1. Landscape Composition Change

The landscape composition in the Huaihe River Basin during 1990–2018 was obtained according to the landscape type images (Figure 3). The results showed that farmland accounted for the major landscape type in the Huaihe River Basin, covering more than 66% of this area; the second was built-up land, covering more than 12% (except in 1990). The area of forest, grassland, and water were relatively small, and their total coverage in the study area is less than 16%. Combined with landscape change rates at 5-year intervals (Table 1), changes to landscape composition in the study area were characterized by the expansion of built-up land and water, the reduction of farmland and grassland, and forest and unused land were variable. From 1990 to 2018, area percentages of built-up land and water increased from 11.9% to 16.3% and 4.1% to 5.3%, respectively; farmland and grassland decreased from 70.3% to 66.8% and 5.4% to 3.9%, respectively.

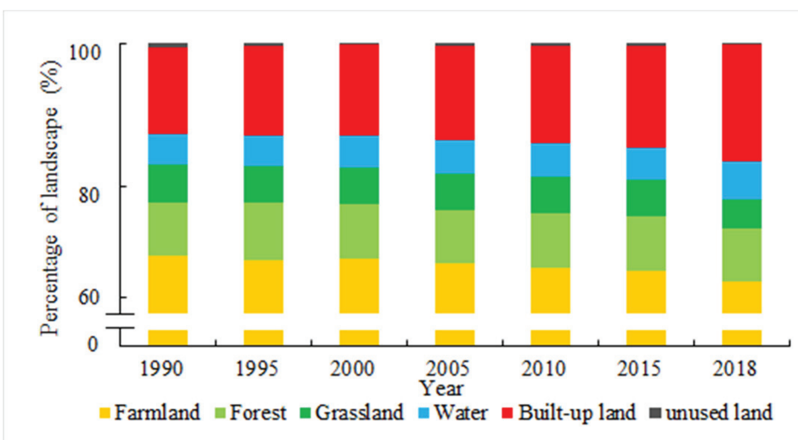

Figure 3. Landscape composition of the Huaihe River Basin during 1990–2018.

The landscape transfer matrix (Table 2) showed that during the study period, the largest reduction in landscape type area was farmland. Around 48,794 km^2 was transferred to other types, mainly to built-up land (33,519 km^2). Less area was transferred to farmland, mainly from built-up land (19,844 km^2). The Grassland area also decreased and was mainly transferred to farmland (6763 km^2) and forest (2760 km^2). Unused land was mainly transferred to water and farmland, and the transfer-out area was three times the transferred-in area, while only part of the area was reserved. The biggest increase in built-up land area was mainly from farmland (33,519 km^2) and grassland (1154 km^2), and the main transfer-out was to farmland (19,844 km^2) and water (1839 km^2). The area transferred out was only half of that transferred in. The water area also increased, mainly from farmland (5919 km^2) and built-up land (1839 km^2). The area of forest was unchanged. In general, changes in landscape types during the study period were dominated by decreases in farmland and grassland and increased built-up land and water. The transition of landscape types mainly occurs between farmland, built-up, grassland, and water.

Table 1. Change rates for different landscape compositions in the Huaihe River Basin in different periods (%).

	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	2015–2018
Farmland	−0.68	−0.71231	−0.07	−0.71	−0.74	−2.39
Forest	6.82	−5.33	−0.01	0.15	−0.26	−1.83
Grassland	−5.15	−0.71	−0.19	−0.20	−0.27	−22.44
Water	2.45	2.74	3.17	0.54	0.56	17.11
Built-up land	2.83	2.14	4.38	3.57	3.76	15.68
Unused land	−28.76	−52.86	92.55	−0.50	1.15	−68.61

Table 2. Landscape transfer matrix of the Huaihe River Basin from 1990–2018 (km^2).

1990 \ 2018	Farmland	Forest	Grassland	Water	Built-Up Land	Unused Land	Transfer-Out Summation
Farmland	190,875	5543	3643	5919	33,519	170	48,794
Forest	5307	14,864	2433	374	900	23	9038
Grassland	6763	2760	5578	600	1154	52	11,329
Water	4095	316	260	6827	942	72	5685
Built-up land	19,844	368	385	1839	8286	24	22,460
Unused land	536	182	113	682	233	74	1745
Transfer-in summation	36,546	9168	6833	9414	36,747	341	

3.2. Landscape Spatial Configuration Change

The landscape indices in the Huaihe River Basin at the landscape level were calculated using Fragstats 4.2 software (Figure 4).

From 1990 to 2018, the AREA_MN, FRAC_MN, and SHDI indices increased, whereas CONTAG and AI indices decreased ($p < 0.05$). AREA_MN increased from 1122 km^2 to 1177 km^2, implying that landscape fragmentation was reduced, and also suggesting that some small landscape patches gradually merged into larger patches. FRAC_MN increased slightly from 1.0173 to 1.0186, indicating that landscape patch shapes gradually became more complex and irregular. SHDI increased, revealing an increase in landscape heterogeneity and evenness. The AI decrease showed that connectivity within the same landscape type was weakened, and the degree of discreteness was enhanced. CONTAG declined from 48.9177 to 47.4691, indicating that the degree of aggregation between patches gradually weakened.

3.3. Ecosystem Services Changes

Based on meteorological, topographic, and landscape type data, ecosystem services of the Huaihe River Basin were calculated using the InVEST models (Figure 5).

Water retention increased from 1990 to 2018 (Figure 6). Total water retention for the study area was 23.4×10^9 m^3 in 1990 and 25.3×10^9 m^3 in 2018. The water retention capacity in the Huaihe River Basin increased from 881.55 m^3/km^2 in 1990 to 954.58 m^3/km^2 in 2018, an increase of about 8.3%. Water retention exhibited a spatial pattern of “high in the southwest and low in the northeast”, and the high-value area gradually increased and expanded from south to north during 1990–2018.

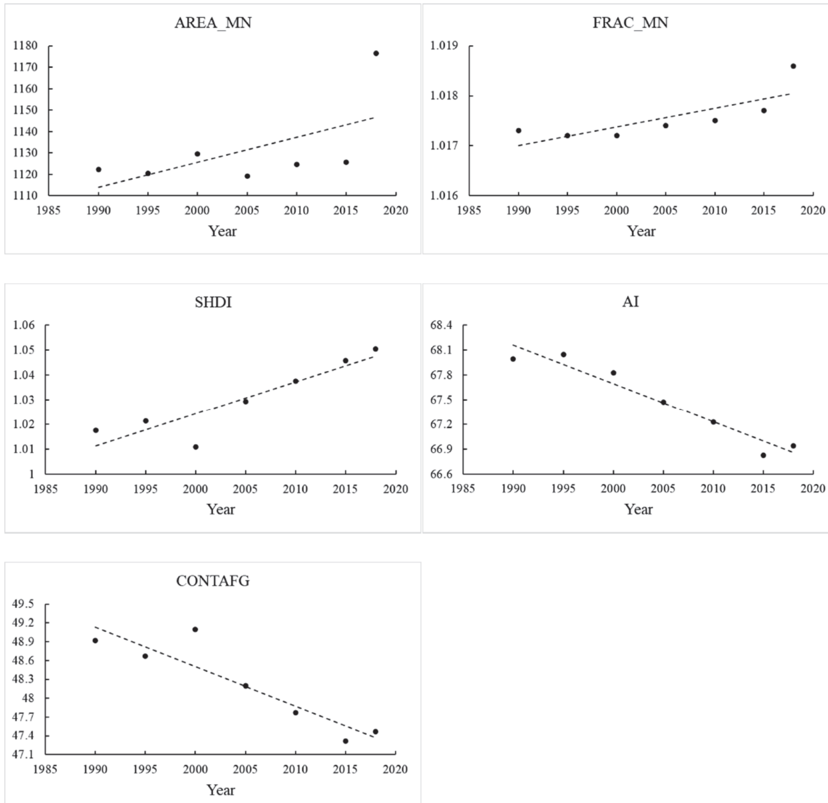

Figure 4. Changes to landscape indices in the Huaihe River Basin from 1990–2018.

Soil retention was 217 × 10^6 t in 1990 and 216 × 10^6 t in 2018, a slight decline over time. The soil retention capacity also slightly decreased (Figure 6), declining from 273.07 t/km^2 to 270.69 t/$km^{2,}$ and the drop was 0.9% from 1990–2018. The spatial distribution of soil retention in the Huaihe River Basin showed that high values were found in the west and northeast, low values in the central and southeast regions, and the spatial distribution area did not change significantly over the study period.

Total carbon storage in the Huaihe River Basin first increased from 71.9 × 10^6 t in 1990 to 73.1 × 10^6 t in 1995, then decreased to 70.0 × 10^6 t in 2018. The carbon storage capacity overall decreased (Figure 6), with a maximum value in 1995 of 87.59 t/km^2 and a minimum value in 2018 of 83.81 t/km^2, a 4.3% decline. During the study period, the highest amount of carbon storage mainly occurred in the western region, with a sporadic distribution in the north, and the change of carbon storage per unit area in different regions was small.

The scoring of biodiversity conservation in the Huaihe River Basin clearly decreased during the study period (Figure 6), from 0.713 in 1990 to 0.681 in 2018, a reduction of 4.5%. The regions with high scores were mainly concentrated in the western and central Huaihe River Basin, and the areas with low scores expanded from 1990 to 2018.

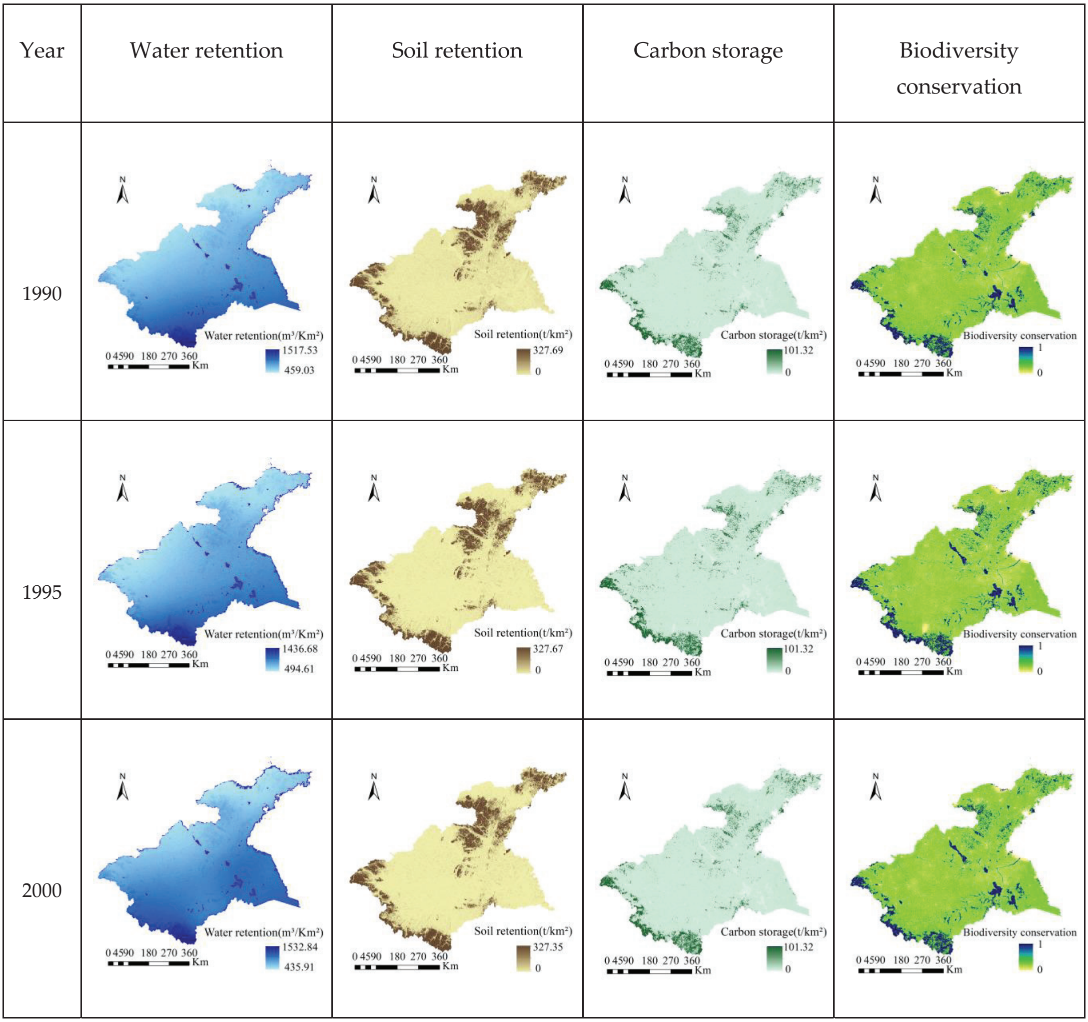

Figure 5. *Cont*.

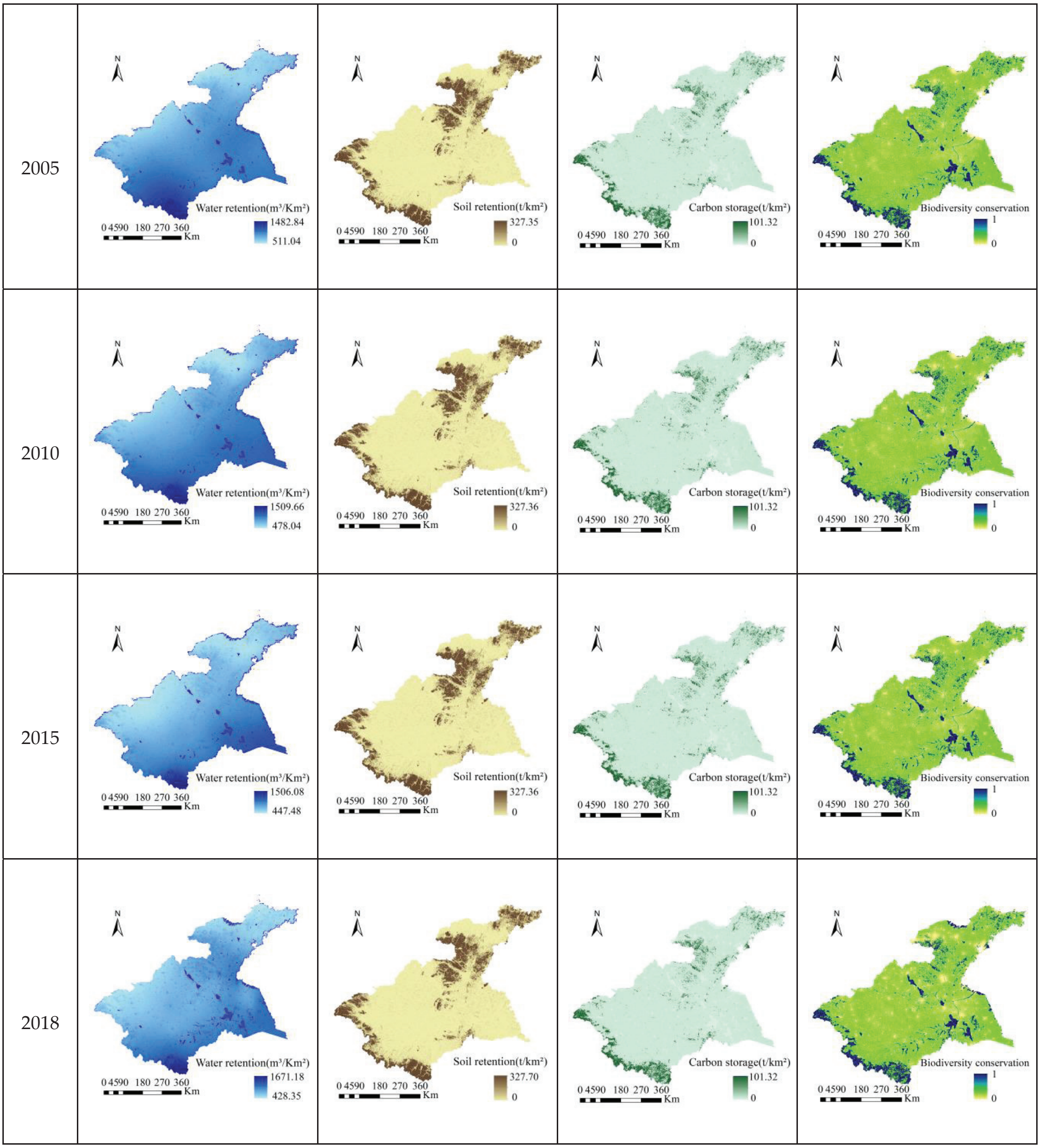

Figure 5. Spatial distribution of ecosystem services in the Huaihe River Basin from 1990–2018.

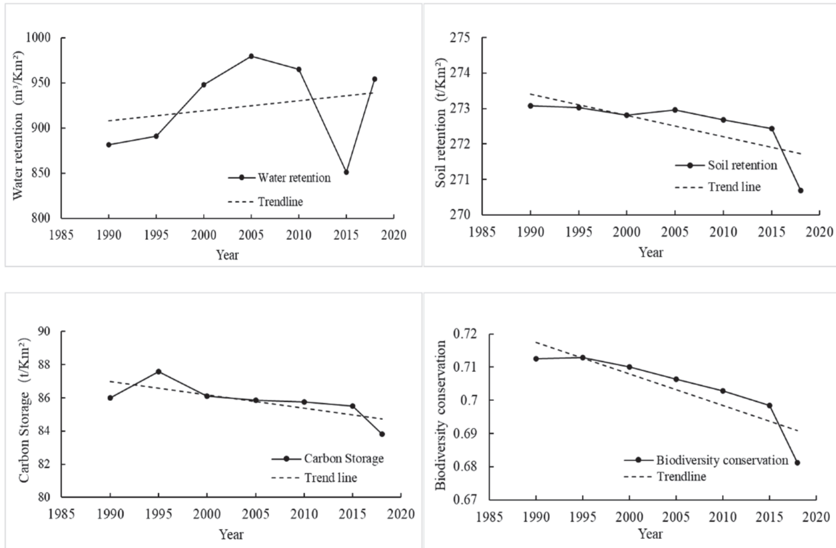

Figure 6. The capacity of ecosystem services in the Huaihe River Basin from 1990–2018.

3.4. Quantitative Relationships between Landscape Indices and Ecosystem Services

3.4.1. Temporal Relationships between Landscape Indices and Ecosystem Services

The temporal relationships between landscape indices and ecosystem services in the Huaihe River Basin were calculated using Spearman correlation analysis in SPSS 22 software (Table 3).

Table 3. Spearman correlations between landscape indices and ecosystem services in the Huaihe River Basin from 1990–2018.

	AREA_MN	FRAC_MN	SHDI	AI	CONTAG
water retention	−0.818 *	−0.899 **	−0.721	0.765 *	0.648
soil retention	−0.259	0.168	0.21	−0.81	0.002
carbon storage	−0.976 **	−0.978 **	−0.735	0.671	0.627
biodiversity conservation	−0.89 **	−0.984 **	−0.869 *	0.833 *	0.794 *

Note: "**" indicates significant correlation at the 0.01 level (two tails); "*" indicates significant correlation at the 0.05 level (two tails).

There was a significant positive correlation between water retention and AI ($p < 0.05$), a negative correlation with FRAC_MN ($p < 0.01$) and AREA_MN ($p < 0.05$), and no obvious relationship with CONTAG and SHDI. There were no obvious correlations between soil retention and the landscape pattern indices. Carbon storage was significantly negatively correlated with AREA_MN and FRAC_MN ($p < 0.01$) and had no obvious correlation with other landscape indices. Biodiversity conservation had clear positive correlations with CONTAG and AI ($p < 0.05$), and negative correlations with FRAC_MN, AREA_MN ($p < 0.01$), and SHDI ($p < 0.05$).

3.4.2. Spatial Relationships between Landscape Indices and Ecosystem Services

This study calculated Moran's I values to explore the spatial relationships between landscape indices and ecosystem services in the Huaihe River Basin from 1990–2018 (Figure 7). Except for FRAC_MN, there were significant spatial correlations between water retention and the landscape indices. However, these correlations gradually decreased. The spatial correlations between soil retention, SHDI, and CONTAG were significant, spatial correlations between AI and AREA_MN with soil retention were weak, and there was no obvious relationship with FRAC_MN. The overall spatial correlations were very stable with little fluctuation. There were stronger correlations between water retention and ecosystem services, except for FRAC_MN, and all slightly declined over time. Biodiversity conservation and all landscape indices show a more or less spatial correlation. The spatial correlations for AI and CONTAG increased, AREA_MN and SHDI decreased, and FRAC_MN was small without fluctuation.

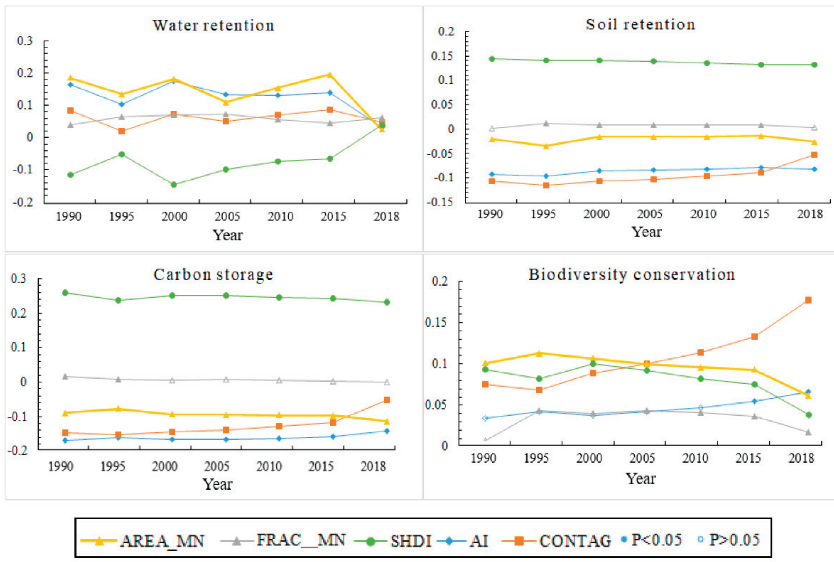

Figure 7. Global spatial correlation coefficient (Moran's I) values between landscape indices and ecosystem services.

4. Discussion

4.1. Change of Landscape Pattern

Due to its rapid economic development and abundant natural resources, the Huaihe River Basin has become an important agricultural and industrial base in China [39,42]. In the present study, landscape type composition analysis, a landscape transfer matrix, and landscape indices were used to explore the changing characteristics of landscape patterns driven by human activities and the environment in the Huaihe River Basin from 1990 to 2018.

In the study period, farmland has consistently made up a high percentage of the total area in the Huaihe River Basin. Although the "Returning Farmland to Forest" policy led to the partial conversion from farmland to forest and grassland [30], the grassland area obviously reduced, and the forest area remained stable (Table 2). The reason for this phenomenon is that a large area of farmland has been converted to built-up land to meet the needs of economic development and urbanization, and the positive effects of the "Returning Farmland to Forest" policy have been weakened by anthropogenic disturbance during the study period. Meanwhile, to avoid the disaster of large floods, a large number of dams, reservoirs, and other water conservancy facilities have been built over the past few decades [37,65], causing in part the transfer of grassland and forest to water.

Five landscape indices (AREA_MN, FRAC_MN, SHDI, AI, CONTAG) were used to further quantify the landscape patterns and their changes due to human activities (Figure 4). The results indicated that there was little change in landscape fragmentation until 2015, after which there was a significant decrease. This indicated that the landscape fragmentation shows a trend of first increasing and then decreasing with urbanization [71].

This change may have been due to the development of agriculture and industries. The built-up area greatly increased and led to small patches of built-up land integrated into the large landscape patches (Figure 2). The result of the "Returning Farmland to Forest" policy allowed some sloping farmland to be converted to forest and grassland, making up larger areas of fragmented grassland and forest [8,16,30]. The increased built-up land area fragmented some of the intact natural landscape, resulting in landscape patches gradually becoming more complex and irregular in shape and weakening the connectivity between patches. Meanwhile, the increased land-use intensity resulted in a large amount of grassland, forest, and farmland being occupied and converted into artificial landscapes, which increased heterogeneity and evenness. This finding is generally consistent with previous studies [4,7,32].

4.2. Relationship between Landscape Patterns and Ecosystem Services

Quantification and mapping of ecosystem services based on integrating scenario analysis provide an efficient and powerful way to evaluate the relative importance and combined effects of factors on ecosystem services [2,27,72]. This study considered the distribution characteristics of the landscape and ecosystem services (Figures 2 and 5) and used Spearman correlation analysis and global spatial correlation coefficient (Moran's I) to further quantify the relationships between landscape indices and ecosystem services. The results showed significant differences in the impacts of landscape pattern changes on different ecosystem services.

In terms of spatial distribution, water retention capacity gradually decreased from south to north and was consistent with the rainfall characteristics of the Huaihe River Basin [73]. Regions of forest and grassland had high water retention, and the building of dams and reservoirs also increased the water retention capacity. The spatial distribution characteristics of water retention capacity showed that climate change had a greater impact on water retention than landscape type change in the study area [27,74,75]. Landscape type-changes play a large role in soil retention: forest and grassland also have a great soil retention capacity [67], and high soil retention capacity was distributed in the west and northeast of the study area, where there was high forest and grassland distribution. However, due to the decrease in forest and grassland area, total soil retention slightly declined. Carbon storage change was also consistent with the change in the natural landscape area, indicating that landscape change had a great impact on carbon storage. The regions with high biodiversity conservation scores were mainly concentrated in the western and central Huaihe River Basin, an area of forest, grassland, and water. However, the grassland loss led to a decline in the capacity of biodiversity conservation over the study period. The results showed that ecosystem services are sensitive to landscape composition change. The loss of grassland and farmland decreases the supply of ecosystem services for human society [15,76]. Moran's I results further showed the impact of landscape spatial configuration on ecosystem services. The results indicated that reduced landscape fragmentation had a positive effect on water retention capacity and biodiversity conservation, reduced connectivity between patches had a negative effect, while reduced landscape fragmentation and irregular patch shapes had negative impacts on soil retention capacity and carbon storage. This finding is shared with previous studies [2,16,77].

In terms of time, the landscape spatial configuration impacts differed. The results showed that reduced landscape fragmentation and connectivity between patches, increased discreteness, and irregularity of patch shapes had negative impacts on water retention. Reduced landscape fragmentation and increased irregular patch shape negatively impacted carbon storage. Increased connectivity had a positive impact on biodiversity conservation, whereas reduced landscape fragmentation and increased patch shapes irregular had negative impacts. There were no significant correlations between soil retention and the landscape indices, showing that soil retention was not easily affected by landscape spatial configuration. This conclusion is different from previous studies; for example, Li et al. argued that irregular patch shape was positively correlated with ecosystem services [2].

Liu et al. demonstrated that enhanced discreteness was negatively related to provisioning and support services and positively related to regulatory and cultural services [12]. Their research was based on a small scale, whereas this study was based on a larger geographic area, illustrating the impact of scale on results.

Compared to spatial correlation, many temporal correlations between landscape patterns and ecosystem services were different, indicating little synergy between the spatial and temporal relationships between landscape patterns and ecosystem services.

5. Conclusions

This study used land-use data, meteorological data, and topographic data to quantify landscape change and ecosystem services and analyze the spatial and temporal relationship between landscapes and ecosystem services in the Huaihe River Basin from 1990 to 2018.

The results suggested that the ecosystem has changed greatly in the Huaihe River Basin from 1990 to 2018. Changes in the composition of the landscape are characterized by a decrease in farmland and grassland and an increase in built-up land and water. The capacity of water retention showed an increasing trend, while soil retention, carbon storage, and biodiversity conservation showed a decreasing trend. This shows that the positive effects of the "Returning Farmland to Forest" policy have been weakened by anthropogenic disturbance in the study area, while the construction of water facilities has promoted the area of water. Maintaining the areas of grassland, forest, and water plays an important role in providing ecosystem services. The capacity of water retention, soil retention, carbon storage, and biodiversity conservation can be improved by increasing the area of grassland and forest. At the same time, the improvment of ecosystem services needs to take into account the spatial and temporal differences in landscape configurations. Therefore, ecological managers and policymakers must consider the impact of landscape pattern changes comprehensively on ecosystem services, and control the disorderly expansion of built-up land to reduce the pressure on the land resources caused by population growth and economic development.

This paper quantified landscape patterns and ecosystem services and their spatiotemporal relationships. We cannot ignore some uncertainties that exist in this study: the InVEST models simplified the simulation of the process, the value of the InVEST results depended on the input data, and as a result, the relative value was not an absolute value, and there was a deviation from the true value. Landscape patterns will change according to spatial scale, and changing spatial scale also can affect the intensity of human disturbance. This may cause the results of our analysis of the relationship between landscapes and ecosystem services to differ from previous studies. Nevertheless, the findings of this study contribute to a better understanding of the impact of landscape change on ecosystem services at a large scale, and we believe this will encourage managers to enhance ecosystem services through landscape pattern planning.

Author Contributions: Conceptualization, Y.Z.; methodology, X.B.; formal analysis, H.W.; investigation, K.W.; data curation, M.Z., C.W. (Chuanying Wang), C.W. (Chen Wang), and Y.L.; writing—original draft, H.W.; writing—review and editing, Y.Z. and X.B.; funding acquisition, Y.Z. and X.B. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The land use data from 1990 to 2018 were downloaded from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 11 December 2021). The rainfall erosivity factor (R factor) was downloaded from the Climate Change Impact Assessment (CLICIA) Group at the Beijing Normal University (https://dx.doi.org/10.12275/bnu.clicia.rainfallerosivity.CN.001, accessed on 13 December 2021). The digital elevation model (DEM) data, temperature, and precipitation data, effective soil moisture data, soil texture data, soil erodibility data, etc., used in this study are not publicly available due to the constraint in the consent.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Exploring the Spatiotemporal Integration Evolution of the Urban Agglomeration through City Networks

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Abstract: Regional integration is a global trend and an integrated region consists of different cities of different sizes and functions, against which researching their organized structure is an important issue when discussing regional coordinated development. So, we construct the city networks, among which cities and their linkages are regarded as nodes and connections, to explore the spatial characteristics of a region and evaluate the integration level. The Yangtze River Delta Urban Agglomeration (YRDUA) is taken as the study area. For city nodes, this paper first evaluates the cities' qualities comprehensively based on the multidimensional indicators during the rapid cities' developmental period from 2005 to 2019. For city linkages, the interactions between different cities are then assessed by the improved gravity model. Then, the city networks consisting of city nodes and their linkages are constructed and analyzed by the social network analysis to deeply understand the orientations and relationships of cities in an integrated region. The results show that the developmental pace of different cities is imbalanced. The overall network of the YRDUA is relatively compact of the city-pair linkages forming the overlapping structure from primary to secondary axes, and different cities have specific functions. However, some small cities do not reach a mutual connection with big cities and face the risk of social resource outflow. In conclusion, attention to the existence of latent hierarchy should be paid to avoid the marginalization of small cities, especially under administrative intervention. The findings can enrich research on cities′ relationship and integration level of the YRDUA, and the specific characteristics of spatial organization paralleling with the leading development of the YRDUA can provide the reference to other regions under the strategy of national regional coordination.

Keywords: regional integration; city networks; spatial structure; regional planning; urban agglomeration

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1. Introduction

The distance shrinks and ties strengthen continuously between cities due to economic globalization, rapid urbanization, transportation facilitation, and so on, under which the urban agglomeration and region emerge. Regional integration was regarded as a developmental law of world cities, the process of increasing density, shortening distance, and reducing segmentation, or one of the most active economic phenomena in the new era [1]. It can be divided into transnational and domestic integration, and the former pursues the common market and mutual development by an economic or political union to eliminate the trade discrimination and other factors hindering economic development, such as the European Union (EU) and Association of Southeast Asian Nations (ASEAN) [2,3]. The latter, which is regional integration, is the hotspot when discussing domestic cities' development. The integrated region usually is one of the best-developmental areas in a country, with the highest industrialization and urbanization level, which often appears in the form of urban agglomeration [4]. Urban agglomeration has become the driving force to promote national and regional growth [5] and is regarded as the major unit for global competition in the future [6,7], i.e., the high quality of urban agglomeration is crucial to both domestic stability and international status. Especially for China whose urbanization has entered a new stage, shortening the difference and achieving coordinated development of cities through regional integration are vital to the urbanization transition.

These realities draw attention to the spatial structure of urban agglomeration, as it reflects the relationship between cities of different functions and the spontaneous spatial organized characteristics rather than the administrative structure of the urban agglomeration, which plays a considerable role in the stability and prosperity level of the urban agglomeration [8]. Cities among integrated regions keep close and frequent contact. On the one hand, the region enlarges the market scale constantly by resources agglomeration, on the other hand, the multi-subjects can realize coordinated development by specialization and division. Thus, targets of improving resources utilization efficiency, giving different industrial facilities to the ground, satisfying employment demand at different levels, and increasing the city's capacity for anti-risk will be achieved, and finally, a prosperous win–win situation is presented. Exploring the characteristics of the spatial structure of the urban agglomeration can provide evidence for interaction between cities and the stage of regional integration for optimizing the regional structure and promoting benign development. As the linkage among cities increasingly strengthens, the location space is replaced by flow space [9], and it has gradually formed a spatial network structure of urban agglomeration with cities as nodes and urban links as chains, which reflects the different combinational relationships of points and lines. The spatial network structure, breaking the traditional hierarchical spatial orderings as visible in the administrative organization [10] and extending the central place theory, becomes a new manifestation form of the spatial structure of urban agglomeration [11]. City networks serve as one of the major conduits for the regional integration process through the exchange of people, products, capital, ideas, etc., so that the region becomes more than the sum of its parts [12].

Many scholars started to research the spatial linkage of different aspects of cities' interaction based on the city networks. This research mostly focused on the transportation network initially, especially premised on the passenger flow and different transportation facilities, such as railways [13–15] and airlines [16–18], or other infrastructure network structures focusing on physical functions [19]. The subsequent literature pays attention to the spatial network structure in different fields, such as tourism [20], environment [21], business [22], and population migration [23]. Some scholars argue that innovation [24], green agriculture [25], knowledge integration [26], etc., are other relevant aspects of city networks. However, the existing research mainly evaluates from a single dimension, which cannot assess the overall spatial linkage of the city network comprehensively, because it is diverse and integrated and covers aspects of the economy, society, environment, and so on, and has its own organizational and dynamic features [27].

Cities' interaction and linkage are the major manifestation of the spatial structure of urban agglomeration, against which the gravity model is applied to evaluate the linkage intensity [28]. The traditional gravity model is majorly used in international bilateral trade, like Newton's universal gravitation law, the trade scale is proportional to the economic scale of a country and inversely proportional to the distance between two countries. The gravity model of trade gradually received the support of theory and became improved [29]. Similarly, scholars believe that the connection among cities can also be explored by it. It is an important tool of city research and is used as the workhorse of empirical research on spatial connection. However, different research has tried to revise it to enhance its applicability in terms of the specific purpose, which has advantages and disadvantages, such as ignoring the direction and asymmetry or using a single indicator to represent the city scale. In addition, those studies usually only focus on the static spatial characteristics of a single year.

Keeping pace with the statistic empirical research, the regional planning and policy have received focus, which jointly promote the development of urban agglomeration. Especially for China whose regional integration has arisen to the height of national strategy, the government always devotes itself to the regional coordinated development. The Yangtze

River Delta Urban Agglomeration (YRDUA), one of the biggest urban agglomerations in China, issued the recent planning outline in 2019, before which it actually already had regional planning in 2010 and 2016. Thus, the YRDUA, which has become the basic spatial unit of policy formulation and implementation about the spatial arrangement of infrastructure, industry, public services, etc., is widely used to research regional integration, which is one of the reasons we select it as our study area.

In summary, the long time-series data in the process of regional integration of the YRDUA (2005–2019) was used to evaluate the cities' comprehensive developmental quality, research the spatial linkage and interaction relationship of cities in the YRDUA, and explore the characteristics of the city network by the social network analysis method. The marginal contribution of this paper is (1) to select the multidimensional indicators and try to be reasonable scientifically, (2) to revise the gravity model to improve its applicability, and (3) to analyze a long period and make the results more all-round, trying to clarify the dynamic feature of spatial linkage, above which we hope to supplement the spatial structure characteristics of the YRDUA precisely and comprehensively, give a reference to regional planning about city orientation, regional cooperation, function zone division, etc., and provide a research framework for other regions.

2. Materials and Methodologies

2.1. Study Area

The YRDUA, located in the east of China and mouth of the Yangtze River, is the most economically active and highly open region in China and one of the six largest urban agglomerations in the world. According to the YRDUA development plan approved by the Chinese government, it consists of 26 prefecture-level cities (Shanghai, 9 cities in Jiangsu Province, 8 cities in Zhejiang Province, and 8 cities in Anhui Province, see Figure 1) and covers an area of 211,700 km^2, nearly 2.3% of China, with a contribution of approximately a quarter of the gross domestic product (GDP). Since the opening and reform, the demand for economic market development triggered city cooperation, which kicked off the integration of the YRDUA that is leading the economic growth in China. Simultaneously, the government always emphasizes the process of the YRDUA integration, with the issuing of a series of policies successively, among which is the recent 2019 "Outline of the Yangtze River Delta regional integration development plan", which expounded the targets and requirements deeply. Among the area, Shanghai is the most developed city, an international megacity, and the engine of the region. Hangzhou, Nanjing, and Hefei are the respective capitals of Zhejiang, Jiangsu, and Anhui Province. As the latest to join the integrated process, Anhui Province shows slower economic development compared to other provinces, indicating the heterogeneity among the inner regions. So, we want to explore the in-depth interaction between different cities, to help promote the further benign development of the region.

2.2. Data Sources

The socio-economic data are from the Statistical Yearbook (2005–2019). The administrative boundaries data are from the Ministry of Natural Resources, China (http://bzdt.ch.mnr.gov.cn/ accessed on 14 December 2021). There are some explanations regarding the data: Chaohu City once was a prefectural city of Anhui Province before 2010, and then was separated into Hefei, Wuhu, and Maanshan City respectively owing to the administrative adjustment. Thus, the data before 2010 was processed in terms of the proportion and added to the above three cities because the collected data in the Statistical Yearbooks before 2010 has Chaohu City separately. Then, the very few missing data were supplemented by department consultation or interpolation method. What is more, we made a distinction between Tai'zhou (in Jiangsu Province) and Taizhou (in Zhejiang Province) to avoid duplication of the name.

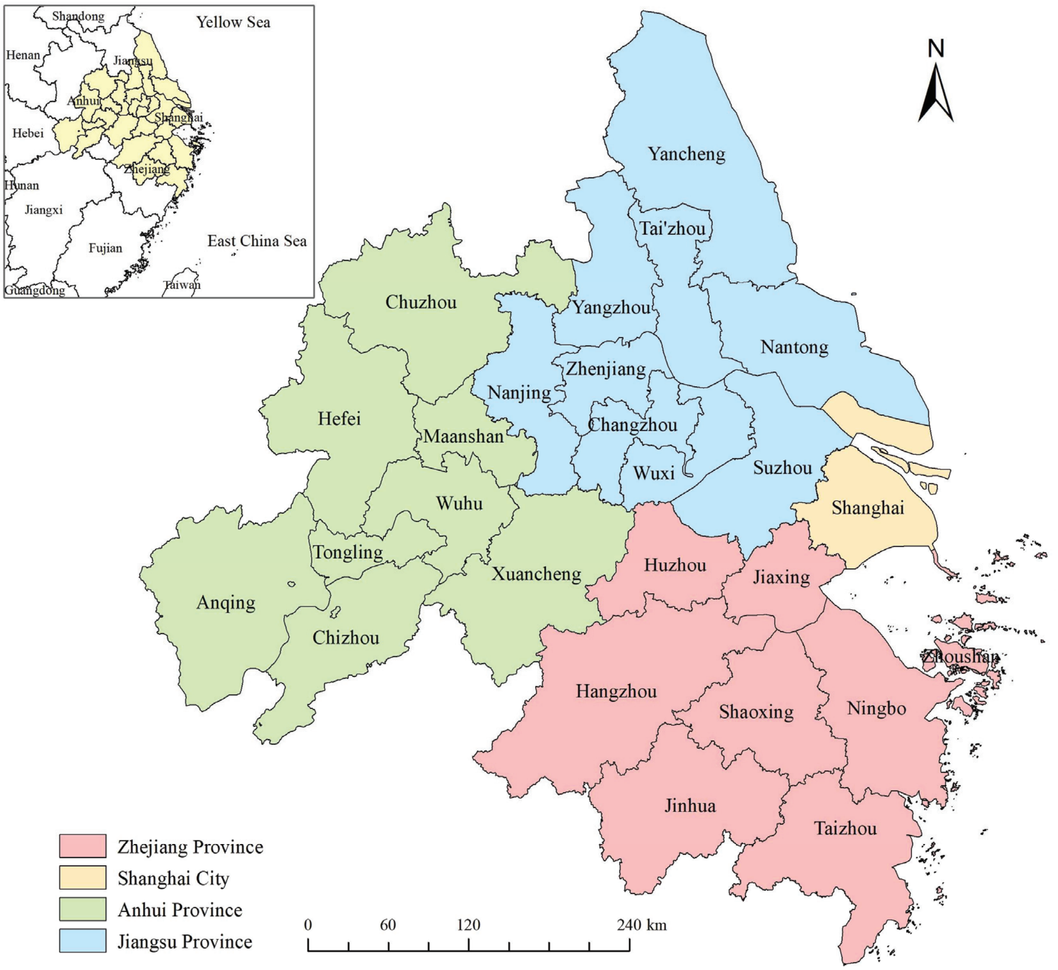

Figure 1. Location and cities of the YRDUA.

2.3. Methods

2.3.1. The Muti-Dimension Evaluation

City networks are multiplex phenomena, and the degree of integration in a certain region often depends on the indicators used to measure it [10]. Moreover, the measurements of regional integration vary with the purpose, area, phase, and background in different literature. Thus, considering the process of regional integration is complex and multi-dimension, and the overall city-linkage characteristics we want to explore, we constructed the multi-dimension integrated evaluation system (Table 1). First, the internal driving force of integration must be social development, including the economy which is also the final pursuit of the whole region undoubtedly, and the vital accelerator knowledge and optimized industry that will boost the economy in the new developmental stage [30]. Factors such as flow capacity reveal the essence of regional integration of the social elements flowing freely and resources utilizing mutually [31]. Public service is one of the important social assurances a city provides [32], and also a vital indicator of the urban comprehensive strength [33]. The environment importance is the brand-new position of urban and regional development against the background of ecology civilization [34].

In summary, four dimensions are constructed to measure the linkage of city networks by reviewing the current literature and shedding light on the rich connotation or essential performance of regional integration. Actually, the "Outline of Regional Integration Development Plan in the Yangtze River Delta" orients that the Yangtze River Delta achieves essential development and make integration progress in the field of science and innovation industry, infrastructure, ecological environment, and public services by 2025 [35], which give the aforementioned evaluation dimensions.

Table 1. Index system to construct city networks.

Dimension	Sub-Dimension	Indicator
Social development	Economy Industry Knowledge	Per capita GDP The proportion of the tertiary industry Number of patents authorized
Physical infrastructure	Factor flow capacity of people Factor flow capacity of goods	Passenger transport by railway and airline Expressway mileage
Public services	Health care Education care Social security care	The number of hospital beds Education expenditure Basic endowment insurance for urban employees
Environmental importance	Environment care	Sewage treatment rate

2.3.2. The Improved Gravity Model

The gravity model was used to research city networks because it can simplify the complicated cities' interactions in reality and is easy to operate, and we use the multi-dimension evaluation results to replace traditional single indicators representing the city scale such as GDP or population [15]. What is more, the traditional spatial distance of the city center cannot represent the real "distance" by anthropic influence. The per capita GDP gap was used by attempting to revise [25]; however, the occasion of similar per capita GDP may lead to the error of infinite gravity in the data process. To a large extent, the city interaction was appearing in the industry resources exchange such as labor flow, trans-city trade, company cooperation, and the head-branch-built enterprises across cities. Given this consideration, to enhance its suitability, the similarity index of industrial structure, which was proposed by the United Nations Industrial Development Organization in 1979 and then improved by Krugman [36] and broadly applied subsequently [37,38], was used to revise the gravity model. Additionally, cities that have similar industrial layouts have frequent flow of factors, i.e., close contacts and tight linkage.

$$Y_{mn} = G\frac{S_m \times S_n}{D_{mn}} \tag{1}$$

$$S = \frac{S_1 + S_2 + S_3 + S_4}{4} \tag{2}$$

$$K_{mn} = 1 - \frac{1}{2}\sum_{j}^{n}\left|Industry_{mj} - Industry_{nj}\right| \tag{3}$$

Here, Y_{mn} represents the mutual gravity value, i.e., the linkage between city m and n. G is the gravitational coefficient, D_{mn} is the spatial distance between city m and n traditionally, which is replaced by the reciprocal similarity index of the industrial structure index K_{mn} between cities. S is the comprehensive evaluation result from the aforementioned four dimensions, and the weight of each index is calculated by the entropy weight method.

$$RI_m = \frac{T_m}{\sum_1^N T_m} \tag{4}$$

Referring to the literature [39], RI_m is relative linkage, namely the interconnectivity to the whole region (0–1), RI = 1 means all the interactions are concentrated on one city code. RI = 0 means code m has no linkage to others and is isolated in the region. A network does not have a hierarchical structure when every node has an equal value of RI. T_m is the total linkage of city m to other cities, i.e., the sum of $Y_{m1}, Y_{m2}, \ldots, Y_{mn}$. N is the total number of cities in a region.

To indicate the asymmetry linkage, the proportion of a city's comprehensive score in the cities pair was used as the gravitational coefficient:

$$Y_{m \leftarrow n} = \frac{S_m}{S_m + S_n} \times \frac{S_m \times S_n}{D_{mn}} \tag{5}$$

2.3.3. Social Network Analysis

The spatial relationship and organization feature of members in a network can be analyzed by the social network analysis (SNA) method that has already been applied in many research fields. SNA has a series of systematic spatial structure evaluation indicators [36,40], such as the whole network characteristics index including network density, network efficiency, network hierarchy, etc.; the individual network characteristics index including degree, closeness centrality, and betweenness centrality of nodes, etc., and structure analysis such as core-periphery division [41].

3. Results

3.1. The Evolution and Connection of Cities

The comprehensive score results are shown in Figure 2 after standardizing the indicators and adding up different dimensions by Formula (2). To quite a large extent, the score can stand for the city's overall quality, and generally speaking, the higher the quality of the city, the stronger the ability to attract regional resources. From the perspective of a single dimension, a high score means that the city has a leading economic development, optimized industrial structure, a strong capacity for science and technology, and is bursting with innovation vitality, which can attract and accommodate the labor and enterprise through the good infrastructure and superior public services. Meanwhile, it can generate a positive space radiation effect and play the role of a regional accelerator, which indicates its important position in the urban agglomeration. Each line in Figure 2 represents the score of each city in the past 15 years, with 26 cities in total. Looking horizontally, the gap between the cities is quite big. Shanghai, as the biggest and most developed city in China, is ahead of any other city each year, with Hangzhou, Suzhou, Nanjing, Ningbo, Hefei, Wuxi, and other developed cities in the YRDUA following behind. The third gradient has Changzhou, Nantong, Yancheng, Yangzhou, Zhenjiang, Tai'zhou, Jiaxing, Huzhou, Shaoxing, Jinhua, Taizhou, and as for the final gradient, except for Zhoushan, others are all from Anhui Province. Vertically, the dynamic change of cities in the same gradient has similar trends. First of all, Shanghai has the maximum increase, showing nearly exponential growth in city quality in the past 15 years and becoming the growth pole of the YRDUA and the whole of China. Although the growth rate of the overall development level of several developed cities is lower than that of Shanghai, it is also large. Most cities show a fluctuating and rising state in the time series. The overall developmental speed of cities with the third gradient is lower than that of the above cities. From 2005 to 2019, their comprehensive scores increased relatively uniformly, and the overall urban status changed little. The increase of the tailed cities is very gentle, with the starting point almost consistent with the ending. These cities are probably in a weak position in the YRDUA, whose social resources may outflow and are attracted by other cities at the same time while enjoying the benefits of coordinated development of urban agglomerations because of the relatively poor ability to provide premium infrastructure and public service and retain population.

The preliminary clarification of different cities' developmental patterns and dynamic growth in the YRDUA cannot reflect the interaction relationship between cities, so the linkage based on the gravity model was calculated by Formulas (1)–(3). Normally, the city pairs with higher qualities and more similar industry structures have a more frequent transfer of population, enterprise, labor, products, etc. And the gravity value will be larger, indicating closer connection and communication. Figure 3 shows the existing spatial pattern of city linkage in the YRDUA, with the following characteristics. (1) The overall city-linkage network of the YRDUA is compact and systematic, with the line of Shanghai–Hangzhou, Shanghai–Suzhou, and Shanghai–Nanjing as the primary axes, through which multiple linkage lines run. The social resources and factors of the node cities are flowing along the axes, and then the great externalities and spatial spillover effect were generated based on the point-axis theory. (2) The secondary close linkage was formed taking Nanjing, Hefei, Hangzhou, Ningbo, and Suzhou as the sub-centers, which are important node cities in the YRDUA. They can accept the radiation effect of Shanghai, and meanwhile play the space radiation function through the encrypted axes, which drive the development of surrounding small and medium-sized cities. (3) Generally, there exists a phenomenon of density in the east and sparsity in the west of the city linkage in the YRDUA, while cities in the west are mostly from Anhui Province. It seems that except for the capital city Hefei, other cities in Anhui Province are isolated in the network, with extremely weak linkage to others. Even the radiation range of the leading city of Shanghai is limited and difficult to cover those little cities which are ranking last in GDP and comprehensive strength in the region.

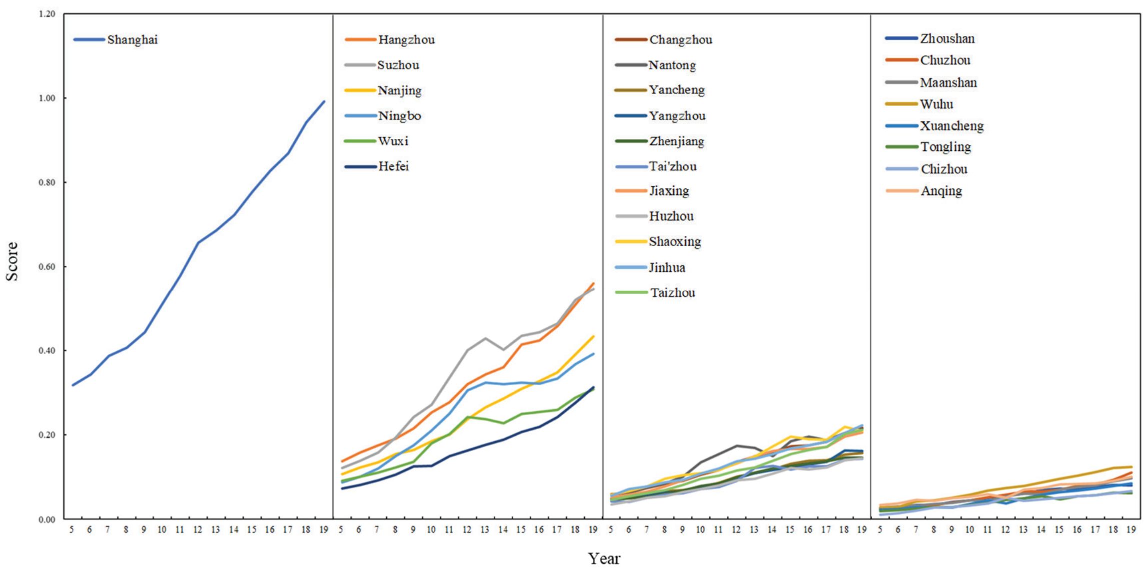

Figure 2. Evaluation of cities' comprehensive quality from 2005 to 2019 in the YRDUA.

After the analysis of city-pair linkage, the node city linked to the whole regions was obtained by Formula (4), representing the connection to all the other cities in the YRDUA and the status in the regional integration (Figure 4). The connectivity of Shanghai is worthy of the highest ranking, owing to the intensive attraction of elements (human, products, capital, information flow, etc.) from the region. The next ranks are Suzhou and Hangzhou, and compared with the quality score, the interconnectivity of Suzhou is larger than Hangzhou, meaning the key position of the conduction function of Suzhou in the network. Tracing the cause, the geographical intermediation of Suzhou made it become an important hub. Moreover, Suzhou, as a large and famous industry city, has a well-developed industry chain, industry clusters, government support, etc., and thus has more interaction with middle-sized and small cities whose manufacturing industry entering Suzhou to enjoy the industrial resources and welfare of labor and skills afterward. In addition, the manufacturing industry heavily relies on transportation convenience. Hence, the centrality of geographical location and developed secondary industry complementarily make Suzhou a core and intermediary node of the YRDUA, which can connect both with Shanghai megacity and small cities below. As for Hangzhou, which is the second city in comprehensive quality, its linkage with Shanghai (0.52) is the highest value (and the lowest pair is Chizhou–Tongling 0.004) in the panel data. This is because the core industry of Hangzhou is a digital economy, and it connects closer with big cities (see Hangzhou–Shanghai 0.52 > Suzhou–Shanghai 0.43 and Hangzhou–Nanjing 0.23 > Suzhou–Nanjing 0.21), while Suzhou is closer with small cities (see Suzhou–Chuzhou 0.055 > Hangzhou–Chuzhou 0.047, Suzhou–Maanshan 0.050 > Hangzhou–Maanshan 0.044). What is more, the interconnectivity of Hefei City, whose city quality ranks the secondary gradient, however, is a bit lower than others. Shown by the gray block in Figure 4, the interconnectivity of the lowest 0–0.1 among the YRDUA and showing nearly no change in the time series, are most of Anhui Province's cities, which keeps line with the results aforementioned and raises concerns about the risk of future development under the siphon effect during the regional integration.

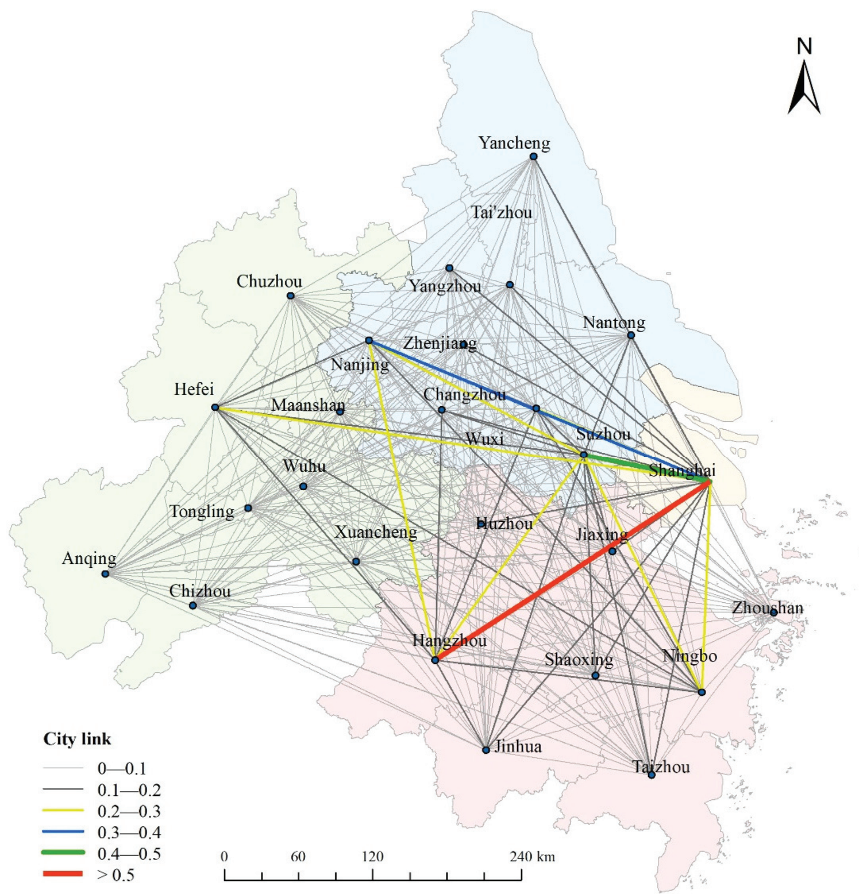

Figure 3. Cities' spatial linkages in the YRDUA in 2019.

3.2. The Structure of City Networks

Then, the city networks are constructed based on the linkage value by the SNA method, trying to give an in-depth and scientific explanation of city connections. In the research of network relationships, the setting of the threshold is key to the properties [42]. Referring to relevant studies [25,43], the linkage is lower than the average of the matrix (Y_{mn}) and is regarded as quite weak and invalid, and others are valid. The network density was obtained as shown in Figure 5 (b), and the whole density is not high with the highest one being 0.308. It may be because eight cities in Anhui Province pull down the overall density by bringing invalid connections with most cities while enlarging the network scale greatly. Then the density is largely increased by the attempt of excluding Anhui Province (seeing Figure 5 (c)) as a new network, which confirms our conjecture.

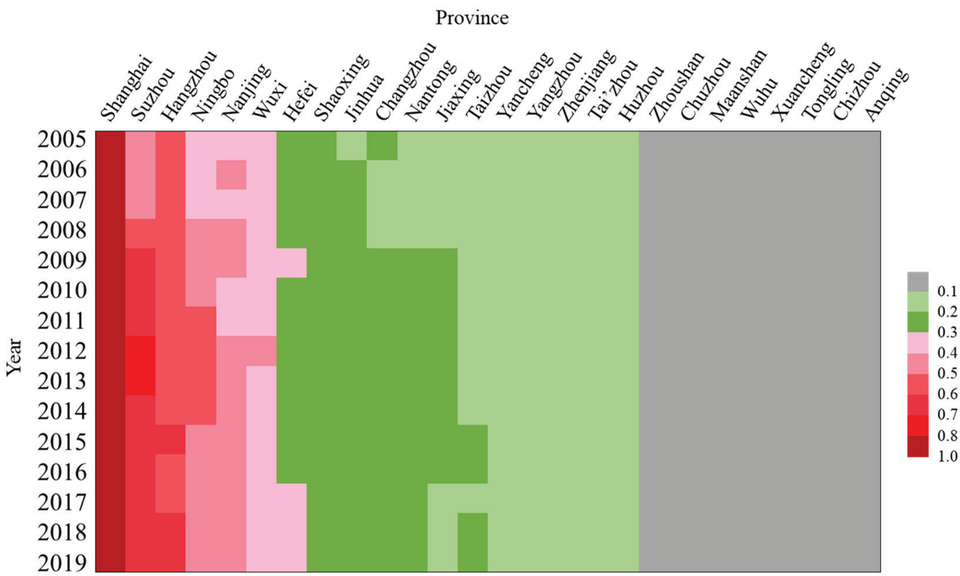

Figure 4. The interconnectivity of cities in the YRDUA.

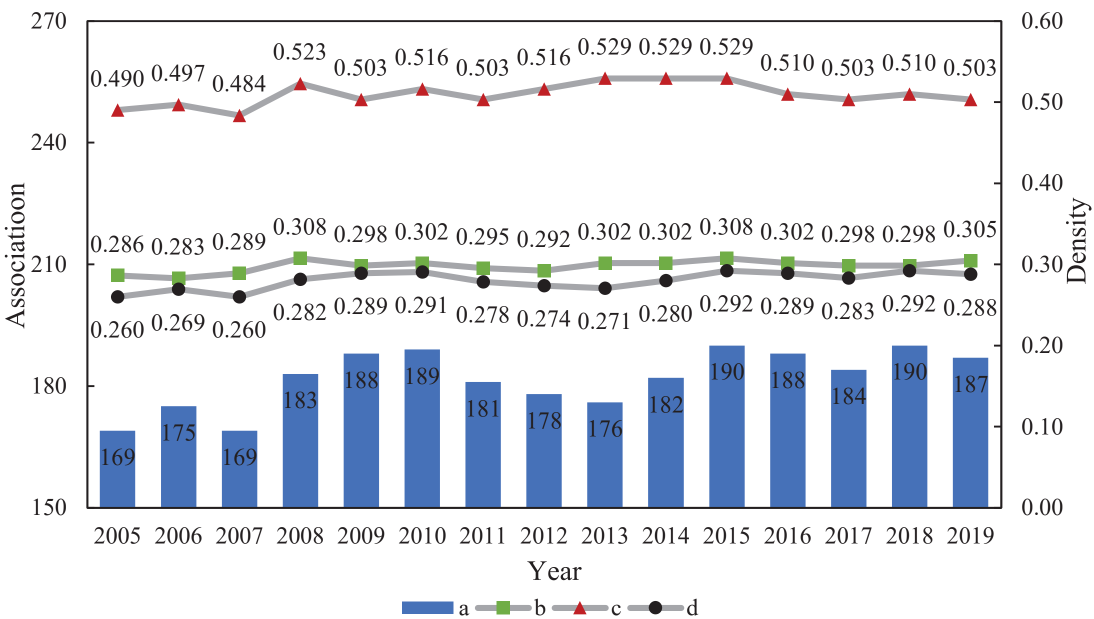

Figure 5. The associations and densities of city networks in the YRDUA.

The asymmetry of city linkage is ubiquitous, and the size and direction of factors flow are unequal between cities [44,45]. In this regard, the gravity coefficient is used to revise and characterize the asymmetry, seeing Formula (5). The network density and valid association giving the directional consideration are recalculated and seen in Figure 5 (a), Figure 5 (d). There are changes compared to Figure 5 (b), and the highest density and association are 0.292 and 190, respectively. From the time series, the directional network density and association appear the changes of increase, decrease, and fluctuating rise, with the overall improvement over a long period. During the past process of regional integration, also the rapid phase of urbanization of China, each city constantly adjusted its development orientation and optimized industrial structure, the relative relationship of city pairs was changing subtly against the alternation of competition and cooperation and the final pursuit of coordinated development. Additionally, there is a reduction considering the asymmetry compared to non-directionality, revealing that some linkages between cities are one-way streets, especially between big and small cities. The social resources are flowing to big cities, and the small cities cannot accept or further utilize the factors like population, technology, products, information, capital, etc., from big cities.

Taking the network relationship in 2019 as an example, the directional network structure is drawn and relevant evaluation indicators of nodes are calculated by UCINET as in Figure 6 and Table 2. The pointing of arrows represents the flow direction of factors, and it can be found that Shanghai, Suzhou, and Hangzhou accept the most associations (with the biggest indegree being 25, i.e., attracting from all cities), followed by Ningbo, Nanjing, Wuxi, and Hefei (range of 17–22). Jinhua, Shaoxing, Nantong, Tai'zhou, Changzhou, and Jiaxing can also accept some flows. The results of closeness centrality in the table give similar explanations of those nodes' status, which expresses the more direct and efficient connection between cities with the smaller value. From the betweenness centrality that reflects the degree of one node controlling the connection with the other nodes, Suzhou is the top, which contacts both big and small cities, signifying its important conduction and control function in the region as analyzed above, playing the vital role in the spatial connection of the YRDUA. Several big cities have achieved bidirectional connections and exchange of resources, with advantageous elements complementing and close connections. However, cities of the outermost circle (with 0 indegree and betweenness) can be accepted by core cities but cannot accept resources from them, meaning no mutual communication has been realized. Those cities have relatively low comprehensive quality scores and are probably the fringe of the YRDUA.

3.3. Dynamic Simulation and Consistence with the Reality

This paper attempts to explore the dynamic spatial linkage characteristics in the sample time series, which can not only clarify the characteristics and questions of the YRDUA integration process further but also test the consistency with the real situation of Chinese urbanization under our research framework.

As shown in Figure 7, the spatial linkage was first established with the megacity Shanghai, which keeps in line with the real situation. Since the improvement of the market mechanism in China, local cities communicate, imitate, and exchange resources with the most open megacity, Shanghai, showing the economic rationality of profit-seeking. In addition, the Chinese government is devoted to gathering resources for the world-class city of Shanghai in time to enlarge the market and raise scale effects in order to develop the Chinese economy and improve its international influence. Developing the big city is one of the major features of Chinese urbanization [45], and caused many practical issues rooted in history, such as uneven city development and rural issues.

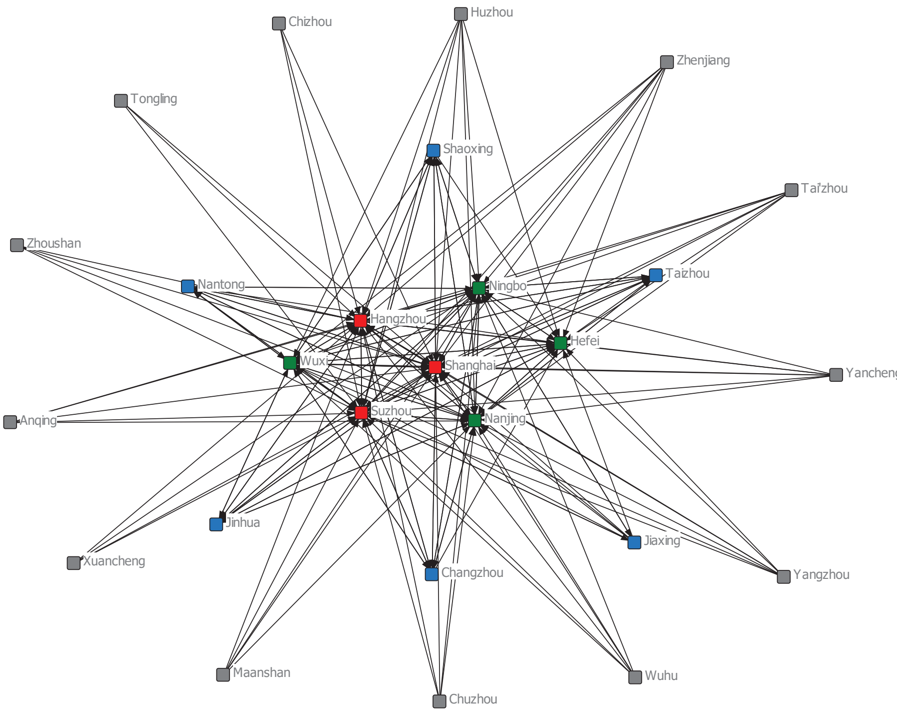

Figure 6. The directional network structure of the YRDUA.

Table 2. Individual index of city nodes in the YRDUA network.

City	Outdegree	Indegree	Outcloseness	Incloseness	Betweenness	NO.
	11	25	52	25	23.96	3
Nanjing	11	22	52	28	15.96	5
Wuxi	11	18	52	32	9.76	6
Changzhou	7	6	56	44	0.00	8
Suzhou	12	25	51	25	36.96	1
Nantong	7	6	56	44	0.00	8
Yancheng	7	0	55	75	0.00	8
Yangzhou	7	0	55	75	0.00	8
Zhenjiang	7	0	55	75	0.00	8
Tai′zhou	7	0	55	75	0.00	8
Hangzhou	11	25	52	25	23.96	3
Ningbo	12	22	51	28	25.96	2
Jiaxing	7	2	56	48	0.00	8
Huzhou	7	0	55	75	0.00	8
Shaoxing	7	6	56	44	0.00	8
Jinhua	7	7	56	43	0.00	8
Zhoushan	4	0	58	75	0.00	8
Taizhou	7	6	56	44	0.00	8
Hefei	7	17	56	33	1.43	7
Chuzhou	5	0	57	75	0.00	8
Maanshan	5	0	57	75	0.00	8
Wuhu	6	0	56	75	0.00	8
Xuancheng	4	0	58	75	0.00	8
Tongling	3	0	59	75	0.00	8
Chizhou	3	0	59	75	0.00	8
Anqing	5	0	57	75	0.00	8

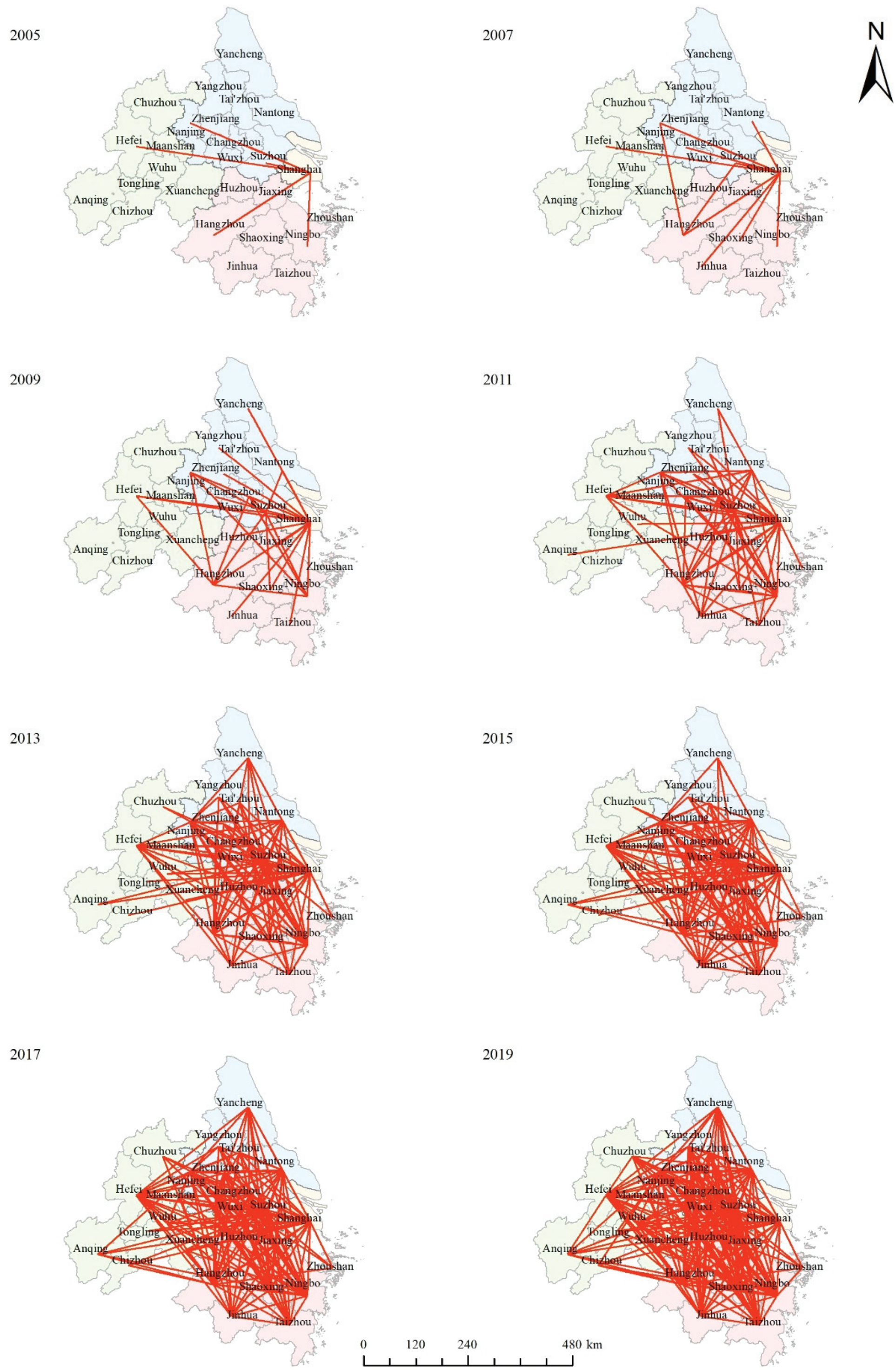

Figure 7. The dynamic linkage of cities in the YRDUA.

Nowadays the national competition platform has gradually become an urban agglomeration against the background of a global trend of regional integration, which the governments are aware of. So, the regional integration process is participated in by the Chinese government heavily, and the local government has played a vital role in promoting regional integration, such as promoting cross-administrative trade, building cross-provincial economic zones, and encouraging enterprises to open up cross-regional markets by increasing investment subsidies and decreasing tax rates [31,46], which greatly help formulate the current regional pattern. This can also be seen from a dynamic view in Figure 7, the early spatial linkage was built comparatively slow and the network is loose, while the connection increased rapidly later and then shows a gentle rise after a relatively complete network was established, which is close to the reality that the coordinated development and integration process of the YRDUA has made big progress since the government started to realize the necessity of cities cooperation and a series of regional planning was implemented.

Big cities gradually became the core nodes in the YRDUA and built spatial linkage after their strength grew enough. The spatial influence scope constantly expanded through the radiation with the core cities as nodes and drove the development of surrounding small cities. The overall network density increased and spatial linkage constantly became close to the dynamic evolution mechanism of connection of Shanghai to big cities, big cities to big cities, and big cities to small cities, thus shaping the firm network structure and improving the capacity of resisting the risk of the whole region and dynamically verifying the regional point-axis theory.

In addition, the spatial linkage spread from east to the west, but the western network is still sparser and shows a slow density increase over time. In reality, the western cities of Anhui Province are late to join the YRDUA from the national top-level planning, which is the dominant force to accommodate the factors of population and industry. In the future, those cities shall improve their own city quality, such as providing good public services by demolishing empty houses to increase the aesthetics and attraction and avoid marginalization [47].

4. Discussion

Much research has tried to evaluate the integration degree of urban agglomeration to assess its socio-economic effects yet it has not reached a consensus because the connotation of regional integration is considerably rich and evolving continuously. Whereas some attempts from the single dimension were made, for example, the relative price variance of products [48,49], the labor wage gap in the market [50], regional economic disparities [51], and the existence of qualitative policy implementation [52,53] have made progress because of its specialized and easy application. In particular, the relative price variance method is used quite frequently, about which scholars nearly have no dispute. However, it only measures the market integration whereas the regional integration involves the whole society and many dimensions, of which economic integration is an important part but not an equal sign. The characteristics of regional integration can be depicted by researching the cities' relationships from a spatial organized structure that can date back to the traditional central place theory, which studied the hierarchy, the relationship between functions, and the regularity of the spatial structure of the urban system in a given region [54]. However, economic geography in an era of global competition poses a paradox [55]. The physical space is displayed by the flow space [9,56], these flows can be labor [57], knowledge [11], pollution emission [58], etc. This paper concentrates on the city itself, integrating these flows from multiple dimensions, which are also recognized as cities' interaction aspects by the planning documents. The new city networks replace the traditional spatial structure, which consists of city nodes, with different developmental cities; city linkages, different city connections, and network space, with the respective orientations of cities in an integrated region. Under this framework (Figure 8), the integration characteristics and questions of the YRDUA were explored in the results, which respond to the situation of regional integration and call for the relevant reality needs.

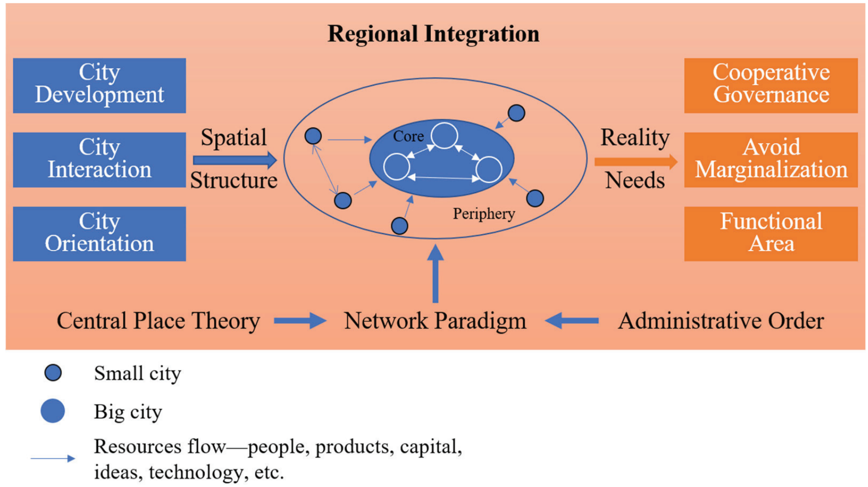

Figure 8. A simplified summarization map of this study.

What is more, except for the inner balance of the YRDUA, the middle and western urban agglomeration in China which are under the incubation stage should get enough attention, too. Additionally, the experience can be drawn upon from the YRDUA with the strategy suit for the local conditions at the same time. The vision of tomorrow is that the medium- and small-sized cities find the reasonable orientation through a characteristic development path, the big cities continue to play the role of radiation, and finally, shape the linkage from city–city to region–region and cooperation of cross-region, and that integrated regions grow synergistically and become the important and powerful tools and space units to participate in international competition. Combined with the urbanization history in China, it shall be considered from the total environment, such as the rural questions, the sustainable urban development issues, the imbalance of city development dilemma, etc.

As analyzed above, the research framework this paper poses is considerably consistent with the reality of the Chinese urbanization process and strategy, and the results can be explained from both theory and real situations. Compared to other assessments focusing on the single dimension (mainly market integration), we consider the multiple aspects of city interactions. Furthermore, the gravity model was modified, in which the previous research just used the physical distance or the error-prone GDP. We believe the framework can also be used to examine the integration characteristic of other regions, and the experiences of the YRDUA can be referenced by others to avoid some unnecessary development issues as they are in the startup stage in China.

However, this paper still has room to improve. The industrial structural index used to evaluate the distance in the gravity model, despite its enhanced applicability, does not express the city interaction always in one way in different phases of regional integration, some scholars argue that industrial isomorphism will cause a waste of resources, influence the efficiency of economic growth, and hinder the integration in the later stage [59]. In addition, the city networks do not totally fit the reality because it is hard to ignore the strong administrative force of Chinese governments, against which the factors flow tends to be frequent among the same province. For the former one, clarifying the resistance of the resource flows between cities in different integration stages can be a solvable avenue, and for the latter, strengthening city cooperation and cross-administrative governance are still strongly advised to advance regional development. In addition, although we consider the city interaction dimension comprehensively, we hope to distinguish the single dimension to further clarify the center of different functions in the region and rich the spatial structural characteristics of the YRDUA in the future. We look forward to deeply researching further macro and micro impacts on urban growth under regional integration.

5. Conclusions

The final pursuit of the regional integration is supposed to be all city members developing synergistically and achieving the Pareto optimality as the region gradually becomes the basic unit of policymaking and implementation due to its status as an accelerator for promoting domestic economic growth and platform of international competition. Exploring the spatial structure can help understand interaction relationships between cities and their orientations in a region. The city network, as a new and recognized paradigm of the spatial structure, was researched widely. Thus, city networks are constructed based on the improved gravity model and analyze the spatial structural characteristics deeply by the SNA method and dynamic study combined with specific time features of the regional integration process. The comprehensive dimensions of city interactions are evaluated from a literature review and real considerations. The YRDUA is selected as the sample area because of the consensus that it is a highly integrated city region. In addition, it indeed updates the regional plan in 2019, indicating the emphasis by governments. The results are:

1. The characteristic of an imbalanced and uncoordinated developmental pace was shown in the process of synergetic development of cities in the YRDUA. Shanghai as a megacity and is far ahead of others, followed by Hangzhou and Suzhou. The more developed cities have a faster developmental speed whereas the weaker the city's strength, the slower the growth of a city. Moreover, cities in the final gradient which rank last and increase slowest among the regions are mostly from Anhui Province, which is the last province to join the regional integration by national planning.
2. For city-pair linkage, the biggest is Shanghai–Hangzhou, then was the cross-connections between several big cities—Hangzhou, Suzhou, Nanjing, Ningbo, and Wuxi. For total interconnectivity to the whole region, Suzhou seems to locate in the core intermediary position and plays the important role of the hub node to connect cities of different levels and perform a conduction function in the YRDUA. The welfare of integration is generated by the transfer of a single center to a multicenter [60]. However, some small cities still do not show a good connection to the region.
3. The city-network density increases after the attempt of excluding Anhui Province, implying the latent hierarchy structure. Meanwhile, the density decreases after considering the directionality of factor flows. Mutual linkages are established to exchange and complement advantageous resources whereas some connections between big and small cities are one way, namely the outflow of social resources from the weak cities, which may easily get into the dilemma of attraction decrease and developmental bottleneck in the follow-up integration process unless there is a brand-new and reasonable orientation.
4. Combining Chinese specific urbanization background, administrative power is the important promotion of the current regional patterns. Although the overall level of the YRDUA is good, the imbalanced characteristic shows the network in the west is sparse and rising slowly, which is owing to the behavior of sparing no effort to gather resources and expand big cities by governments.

Hence, in the future, the small- and medium-sized cities should find reasonable orientation through a characteristic development path, especially under the reality that the hierarchical impact of the administrative organization imposed by the spatial organization of the Chinese state is still evident. Moreover, the attention of the central and west regions in China shall be paid to promoting cross-region growth and cooperation. Thus, there is a necessity for the improvement of the mechanism of regional integration from macro and micro aspects against the game of the central and local governments in the top-down administrative system.

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Article

Does Network Externality of Urban Agglomeration Benefit Urban Economic Growth—A Case Study of the Yangtze River Delta

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Abstract: Scholars have conducted a large number of empirical studies on agglomeration externalities and network externalities at the urban scale, but there are relatively few studies at the urban agglomeration scale. For the integrated development of the Yangtze River Delta (YRD), analyzing the impact of network externalities and agglomeration externalities on urban development can provide academic references for the integrated development of urban agglomerations. The results show that: (1) From 2000 to 2010, the average GDP growth rate of the cities in the YRD region showed a rapid growth trend but began to slow down after 2010, showing an outward spatial distribution pattern. (2) From 2000 to 2020, the growth rate of Shanghai's investment in cities in the YRD showed a downward trend and an outward spatial diffusion. The growth rate of investment within the YRD showed a slowing trend from 2000 to 2015 and increased after 2015, showing a spatial distribution from northwest to southeast. From 2000 to 2020, the growth rate of investment from other cities in China to cities in the YRD showed a continuous upward trend, and spatially formed a distribution characteristic from northwest to southeast. (3) The growth of internal investment in the YRD and that of other cities across China can accelerate urban economic growth, and the growth of internal investment in the YRD has a greater role in promoting economic growth, indicating that the "agglomeration externalities" and "network externalities" at the urban agglomeration scale both can promote urban economic growth, but the effect of the "agglomeration externalities" within the urban agglomeration is more obvious. (4) The growth of investment in the core city Shanghai does not play a significant role in the long-term economic growth of cities in the region.

Keywords: network externalities; agglomeration externalities; the Yangtze River Delta; urban agglomeration; urban connection

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1. Introduction

The central place theory has laid a theoretical foundation for the development of the urban system. Through continuous in-depth research, scholars have derived classic regional and urban theories, e.g., the "growth pole theory" and the "core-periphery theory". In early research of the urban system, the object was often confined to natural geographical units or independent administrative areas. Cities were assumed to exist in isolation and regarded as "spaces of places" in closed areas [1]. With economic globalization and regional integration and the rapid development of infrastructure construction and information technology, the connection between cities is getting closer and closer. The subsequent flows of various elements have accelerated, and an urban network centered on cities of different sizes has gradually formed. The dominant urban form has gradually changed from "spaces of places" to "spaces of flows" [2,3]. Since Castells put forward the "spaces of flows" theory in the 1990s, research on cities and regions has begun to shift from a vertical hierarchy system to a network system [4]. The development of cities depends not only on their functions and characteristics but also on inter-city relations and spatial spillover effects [5–7]. Trying to analyze urban issues from a wider perspective, the proposal of the "spaces of flows" theory and related research have made the research on regional and urban development no longer confined to a closed area. Meanwhile, they have broken the boundaries and scales of traditional urban research and shifted the perspective of urban studies from hierarchy to network connections [8,9]. With the deepening of research, urban research has gradually moved from "agglomeration externalities" to "network externalities" that cross geographical boundaries [10]. Agglomeration economy usually refers to the agglomeration of similar industries or complementary industries in adjacent geographic spaces to form industrial clusters or interdependent economic networks due to the spatial agglomeration of economic activities. Rosenthal et al. believe that agglomeration externalities refer to the spillover effects obtained by economic agents from geographical proximity [11]. Analyzing from the perspective of agglomeration and economies of scale, scholars pointed out that the expansion of urban scale can increase the benefits brought by agglomeration [12–14]. However, geographical proximity is not the only reason for economic externalities; interactions between geographically nonadjacent economic agents can also generate externalities [15]. Capello introduced network externalities into the research of urban networks, pointing out that cooperation and participation between localities form network advantages, and the existence of inter-city functional networks can create synergy and complementarity [1]. In recent years, the issue of agglomeration externalities and network externalities has received increasing attention, and their impact on urban development has become the focus of research on urban network externalities [15]. Since the introduction of network externalities, scholars have analyzed the influence of urban network externalities on economic development and the mechanisms from different perspectives, and compared the impact of network externalities and agglomeration externalities [15]. The externality research around urban agglomeration focuses more on the different forms of externalities, measures the different dimensions of externalities, and describes less when it comes to larger scales of externalities [16].

In general, there are few studies focusing on the impact of network externalities and agglomeration externalities on urban economic growth at the urban agglomeration scale, and there is a lack of comparative studies between the two. Under this background, this paper attempts to conduct research at the scale of urban agglomerations and empirically analyze the impact of network externalities and agglomeration externalities on urban development from the perspective of externality theory. Specifically, this paper aims to answer the following questions. Firstly, what is the spatial pattern of network externalities and agglomeration externalities at the urban agglomeration scale? Secondly, how do they promote urban economic growth? Finally, are there differential impacts between network externalities and agglomeration externalities on urban economic development?

In recent years, China has proposed to take urban agglomerations as the main body to build an urban pattern of coordinated development of cities of different sizes, and further enhance the level of integrated development of Beijing–Tianjin–Hebei, Guangdong–Hong Kong–Macao, the Yangtze River Delta, and other regions that are included in the national strategy. Urban agglomerations have become economic growth poles and core regions in development. In December 2019, the "Outline of the Yangtze River Delta Regional Integrated Development Plan" was released, and the Yangtze River Delta (YRD) regional integration strategy entered the implementation stage. It is one of the regions with the most active economic development, the highest degree of economic openness, and the greatest innovation capacity in China. Compared with the connections in closed areas, this paper adopts the perspective of externality to examine the regional connections of urban agglomerations, which is of great significance. Based on this, this paper intends to analyze the impact of network externalities and agglomeration externalities on urban development at the urban agglomeration scale. Specifically, 41 cities in the YRD are selected as the research objects. This paper uses factors such as corporate investment in the YRD and in other cities across the country to characterize the influence of network externalities and agglomeration externalities on urban development. By analyzing their impact on the economic growth of cities in the YRD from 2000 to 2020, this paper aims at clarifying the impact of network externalities and agglomeration externalities on urban economic development and providing case support from the scale of urban agglomerations. On one hand, this paper provides new evidence for urban economic growth at the scale of urban agglomerations, and on the other hand, it provides a basis for decision-making for the development of regional economic integration.

The structure of the remaining paper is as follows: the second section presents the literature review; the third section presents research areas, data sources, and methods used in this study; the fourth section present the results of the empirical analysis; the fifth section is the conclusions and discussion.

2. Literature Review

Since the Industrial Revolution, the functional boundaries of cities have changed significantly with increased mobility and the development of information technology. The central place theory of Christaller focuses primarily on explaining the distribution, size, number of cities and towns, and location of economic activity [15]. Based on the central place theory, classical regional and urban theories such as polarization-diffusion have emerged. On the other hand, the empirical research of the urban systems dissects the organization of urban systems and the nature of urban networks [17,18]. Urban systems are defined as regionally, nationally, and globally connected and interdependent urban spaces [18]. With the incorporation of the network dimension into external economic and urban growth studies, urban studies have shifted from agglomeration externalities to network externalities. The interplay between economic entities that are not spatially adjacent will also generate externalities, which some scholars call "urban network externalities" [1], "regional externalities" [19],"externality fields" [20], and "borrowed size" [10,21].

As early as the 18th century, agglomeration economies were formed in some countries and regions, in which the same (similar) industries or complementary industries agglomerated in specific and adjacent geographic locations to form industrial clusters or economic networks [22]. Duranton and Puga summarized three micro-mechanisms of the agglomeration economy: "sharing" of intermediate inputs and public facilities; "matching" between market entities and factors; "learning effect" of knowledge interaction and technology diffusion [23]. Agglomeration theory gives an explanation of urban economic development from a microscopic level. Agglomeration externalities refer to the additional benefits obtained by economic actors from being located in agglomeration areas under these mechanisms, including cost reduction and income increase brought by factor sharing, and learning opportunities brought by knowledge spillovers [11]. In addition, scholars of new regionalism believe that knowledge spillovers are also affected by social embeddedness, cultural proximity, and institutional thickness [24], pointing out their regional features [25].

Development of transportation and information technology has strengthened the endogenous correlation of economic development between cities, and "spaces of flows" constituted by information flow, technology flow, human flow, and logistics have integrated cross-regional structures. Agglomeration economies are no longer limited to isolated space. Local places are absorbed into the inter-city network flows. From the perspective of the global system, the embeddedness of most cities in domestic and international city networks has a greater effect on city performance, compared with the impact of a city's scale, that is, city status is determined by its position in the network, rather than local agglomeration capabilities [26]. Capello first proposed the concept of "urban network externalities", pointing out that network economic cooperation participants can obtain the advantages of network externalities [1]. Network externalities may stem from economies of scale, knowledge effects, transaction cost reductions, and organizational advantages [27]. The agglomeration externality decreases by distance, while the network externality is not strictly confined in space and changes with the strength of the urban functional relations [10,28].

Scholars have conducted a lot of research on the impact of network externalities and agglomeration externalities on urban development. One view holds that agglomeration externalities are more important to economic growth than network externalities. For example, Biox et al. incorporated agglomeration economies and network externalities into urban growth models to explain why sectoral employment growth in one city is higher than in another city. The result showed that the agglomeration economies' coefficient is greater than the network externality coefficient [27,29]. Taking Japan's high-speed rail as an example, Jetpan Wetwitoo et al. studied the relationship between high-speed rail (HSR) and regional economic productivity, and found that network externalities and agglomeration externalities both promote regional productivity, and network externalities were significantly weaker than agglomeration effects [30].

Other scholars believe that network externalities can substitute agglomeration externalities to some extent. For example, McCann and Acs believe that in different stages of globalization, the importance of agglomeration externalities and the relationship between urban scale and economic development will change. Cities' connections to regions and the world matter more than their size [26]. Chenghui Tang et al. analyzed the heterogeneous impact of HSR on the innovation performance of Chinese cities, and found that urban innovation performance can be improved through both network externalities and agglomeration externalities, and compared with the latter, network externalities have a greater impact [31]. Yin Huang et al. believe that urban network externalities have a significant role in promoting urban economic development, and compared with agglomeration economies, urban network externalities do not depend on the geographic proximity of cities, but rather relies on connections in the network, which can have cross-spatial spillover effects [32]. Jiaming Li et al. explored the impact of strategic emerging industries (SEIs) on urban economic growth in mainland China, arguing that network externalities are usually more important than agglomeration externalities [33].

In addition, there is a growing view that there is a complementary relationship between network externalities and agglomeration externalities, and the two provide market participants with a complimentary benefit [5]. As Cabus argues, there are two complementary components in explaining the geographic impact of external economies: agglomeration economies driven by geographic proximity, and network externalities, where the latter is linked to the network itself and influenced by geographic competition and capabilities [34]. In a word, network externality research makes up for the limited spatial scope of agglomeration externalities and the lack of measurement of the relationship between cities and extends the theoretical connotation of urban research.

On the other hand, under the background of globalization and marketization, cross-regional enterprises and metropolises are actively integrating into the urban network, and the network system pattern is profoundly shaped by market mechanisms, culture, and institutions within the region. The agglomeration effect performs at a larger spatial scale [21]. In addition to the urban scale, network externalities have multiple spatial scales such as "global scale", "national scale", and "regional scale" [35,36]. At present, scholars have conducted a large number of empirical studies on network externalities and agglomeration externalities at the urban scale, but relatively few studies have been conducted at the urban agglomeration scale. The empirical study on the impact of network externalities and agglomeration externalities on urban economic growth at the urban agglomeration scale has important policy-reference value for promoting the integrated development of urban agglomerations.

The agglomeration externalities at the urban scale refer more to the close upstream and downstream relationships between enterprises, knowledge and information spillovers, and large-scale labor markets [30,37]. Due to the proximity of space, enterprises in different industries generate new ideas due to the spatial gathering of industries and people, and promote local economic development [38]. In contrast to industrial clusters' cooperative networks based on spatial proximity, network externalities emphasize the benefits of information or financial linkages beyond regions and cities, highlighting the effects of nonlocalization [33]. The agglomeration externality at the urban agglomeration scale means that cities within the urban agglomeration generate agglomeration economies through resource sharing, mutual competition, and mutual learning, thereby promoting spatial spillovers. Cities within urban agglomeration will continue to attract the spatial agglomeration of factors of production and economic activities, and continue to expand the agglomeration. The network externalities at the urban agglomeration scale means that with the strengthening of transportation and economic links, cities within the urban agglomeration acquire externalities outside the urban agglomeration, share resources through network channels, and learn from each other. With the help of the trend of networking, cities absorb the external economic factors of urban agglomerations, improve resource allocation efficiency, match resources on a larger spatial scale, and improve production factors' allocation efficiency, thereby generating network externalities and promoting economic development.

The overall framework of this study is shown in Figure 1. The concepts of agglomeration economy and network externalities are compared at the urban agglomeration scale to explain the theoretical impact mechanism of externalities on economic growth. The basis for the formation of urban agglomerations is the close connection between cities in the region. Under the background of regional integration, the cost of transportation and connection within the urban agglomeration is reduced, and industrial division of labor and agglomeration advantages are formed between cities. Different from the analysis of externalities at the urban scale, the urban connections within the urban agglomeration are taken as the representation of agglomeration externalities at the urban agglomeration scale. Similarly, cities can acquire development elements in larger areas outside the urban agglomeration; thus, the urban connections outside the urban agglomeration are regarded as a representation of network externalities. The agglomeration externalities at the urban agglomeration scale are spatially restricted by the urban agglomerations, while the network externalities are not; agglomeration externalities are mainly manifested in the internal connections of urban agglomerations, while network externalities involve cross-regional connections. It is worth mentioning that comparing the impact of an agglomeration economy and network externalities on urban economic growth at the urban agglomeration scale requires data verification in a large number of urban agglomeration areas. Limited by the availability of data, this paper only takes the YRD region as an example to carry out empirical analysis, and the conclusions obtained are only applicable to the region equivalent to the development stage of the YRD in China, so the above problems can only be partially analyzed. A more complete conclusion awaits regional data acquisition and corresponding empirical analysis at different development stages.

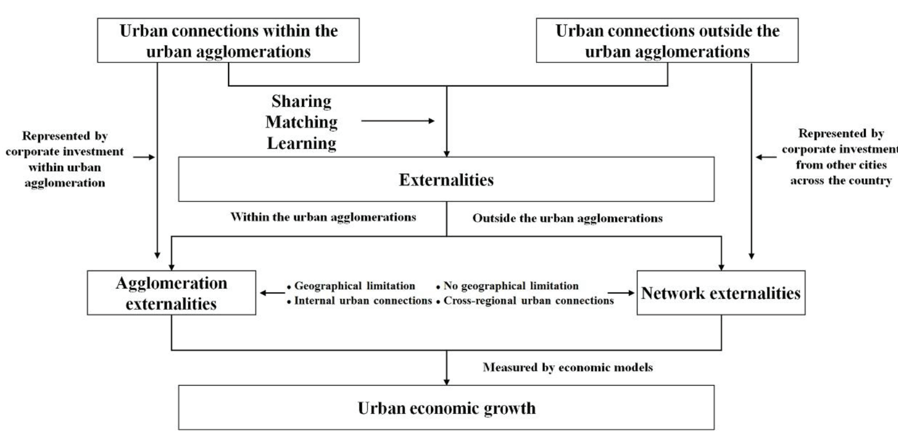

Figure 1. The framework of the research on the externalities of urban agglomerations.

3. Research Areas and Research Methods

3.1. Research Area and Research Period

The YRD region includes 11 cities in Zhejiang Province, 13 cities in Jiangsu Province, 16 cities in Anhui Province, and Shanghai, which comes to 41 cities in total (Figure 2). By the end of 2019, the YRD had an area of 358,000 square kilometers and a total population of 227 million. In 2020, the GDP of the YRD was 24.5 trillion yuan, and the urbanization rate of the permanent population exceeded 60%. The YRD accounts for less than 4% of the country's land area, generating nearly 1/4 of China's total economic output and 1/3 of China's total import and export volume. The research period of this paper is 2000–2020, with five years as a period; thus, the research period was divided into four periods: 2000–2005, 2005–2010, 2010–2015, and 2015–2020. The administrative divisions are unified according to the administrative boundary of 2020. Since Chaohu began to be managed by Hefei in 2011, it was merged into Hefei.

Figure 2. The study area.

3.2. Data Source and Processing

The economic data were mainly obtained from the China City Statistical Yearbook 2001–2020, Shanghai Statistical Yearbook 2001–2020, Jiangsu Statistical Yearbook 2001–2020, Zhejiang Statistical Yearbook 2001–2020, Anhui Statistical Yearbook 2001–2020, China Population and Employment Statistical Yearbook 2001–2020, YRD Cities Yearbook, Shanghai 1% Population Sample Survey Data, Anhui Province 1% Population Sample Survey Data, Zhejiang Province 1% Population Sample Survey Data, Jiangsu Province 1% Population Sample Survey Data, and the statistical yearbooks, government work reports, and statistical bulletins of cities. The basic geographic data was obtained from the 1:4 million Chinese terrain database map, and the boundary is extracted and processed by ArcGIS. The data of enterprises' investments during 2000–2020 were obtained from the registration data of Chinese industrial and commercial enterprises, and it is screened from the massive investment data across the country. The amount of investment is used as a measurement indicator, and the investment linkages between enterprises are projected as the linkages between cities, which measures how cities invest in each other. Among them, there are 5765 nonlocal investment linkage flows in the YRD, and 133,898 nonlocal investment linkage flows in cities across the country (Table 1).

Table 1. The basic situation of investment linkage flows between cities in different places.

Year	Number of Investment Linkage Flows in the YRD (Bar)	Number of Nonlocal Investment Linkage Flows in Cities across the Country (Bar)
2000	739	12,157
2005	931	16,522
2010	1176	23,342
2015	1390	33,918
2020	1529	47,959
Total	5765	133,898

3.3. Methodology

This paper uses a combination of descriptive analysis and quantitative analysis to explore the impact of internal and external economic investment on urban economic growth in the YRD region. When researching on city-scale network externalities and agglomeration externalities, most choose to use industrial location entropy [39], economic agglomeration degree [31], Herfindal coefficient [40], and other indicators to measure agglomeration externalities, and use corporate linkages [41], railway linkages [32], university and hospital linkages [42], the number of cities participating in regional meetings, and the sum of the number of partner cities [1], etc., to measure network externalities. Among them, the World city network (WCN) transforms the connection at the company level into the connection between cities to research on urban spatial connection. WCN analyzes the central or peripheral status of cities in the global economic network based on enterprise connections in the global economy [43–45]. Scholars have used enterprise networks to analyze urban linkages, explaining the clustering patterns in the network and the processes behind urban linkages [46]. Drawing on the above analysis methods, this paper adopts the enterprise connection to represent the inter-city network connection. Furthermore, the YRD region is closely connected with other international cities in addition to the connections within the urban agglomeration and with domestic cities. Due to the availability of data from multinational companies, this paper mainly considers urban connections within the country.

Different from the analysis at the city scale, the agglomeration externality and network externality measurement indicators at the urban agglomeration scale are represented by the investment in a city within the urban agglomeration and the investment in the YRD cities by other cities across the country. Considering the influence of Shanghai as a core city on other cities in the YRD region, the investment of the core city (Shanghai) in cities is regarded as the core explanatory variable. In terms of specific data processing, this paper extracts the amount of Shanghai's investment in each city in the YRD over the years as the investment from the core city (Shanghai), the amount of the investment of all cities in the YRD region to a city as the investment within the urban agglomeration, and the amount of investment of all cities in the country except the YRD as the investment of other cities in the country to the YRD.

The description part mainly visualizes and compares the spatial distribution of economic indicators in the YRD region. The quantitative analysis part mainly uses the investment within the YRD, the investment in the YRD cities by the core city (Shanghai), and the investment in the YRD cities by other cities across the country as the core explanatory variables to test the impact of the three on urban economic growth.

3.3.1. Panel Data Regression Model

Compared with cross-sectional data, panel data has the following advantages: First, they can build a fixed-effects or a random-effects model to solve the estimation bias problem. Second, panel data can provide more dynamics information about individuals, from cross-section and time dimensions. Taking the core explanatory variable of this study (the urban investment variable, as an example), cross-sectional data can only show the differences between cities, but the investment amount to a city may change a lot with time, and the time dimension provides information that cannot be ignored for this paper. Third, because panel data has information in both time dimension and cross-sectional dimension, the sample size is usually larger, which helps improve estimation accuracy.

Based on the long-term economic growth model [47], this paper adds urban investment explanatory variables to test the impact of urban investment on urban economic growth. Considering that GDP represents socioeconomic development, innovation, and technological status [48,49], this study uses the GDP growth rate to reflect urban economic growth. This paper studies the urban economic growth in the YRD region from 2000 to 2020. The initial economic characteristics were adopted as the explanatory variables, and the average annual growth rate of GDP in the four periods from 2000 to 2020 (ΔGDP) was adopted as the explained variable. The basic form of the estimated model is:

$$\triangle GDP_{it} = a + \beta_1 inv_{it} + \beta_2 GDP_{it} + \beta_3 fix_{it} + \beta_4 lab_{it} + \beta_5 fdi_{it} + \beta_6 ame_{it} + \beta_7 urban_{it} + \beta_8 edu_{it} + e_{it} \quad (1)$$

$$e_{it} = a_{it} + u_{it} \quad (2)$$

In the model, i represents different cities, t represents different times, ΔGDP_{it} is the GDP growth rate of city i in a period t, e_{it} is the stochastic error term, a_{it} is the disturbance term that changes with the individual, u_{it} is the disturbance term that changes with time, and α is the intercept of the model. The inv_{it} includes the average annual growth rate of Shanghai's investment to city i, that of investment to city i by all cities in the YRD, and that of investment to city i by other cities across the country. Control the initial level of economic development (GDP_{it}), capital (fix_{it}), labor (lab_{it}), economic openness (fdi_{it}), public service quality (ame_{it}), urbanization level($urban_{it}$), human capital (edu_{it}), etc. in the economic model. On one hand, this paper adopts an economic growth model, and the initial value of the independent variable (lag term) is hardly affected by further urban growth, thus avoiding the endogeneity problem caused by reverse causality [50]; on the other hand, it depicts the long-term impact of initial urban characteristics on urban growth.

To better understand the impact of urban investment on urban economic growth, the investment is divided into the investment of the core city, within the urban agglomeration, and outside the urban agglomeration. Combined with the existing relevant research, comprehensively considering the representativeness of variables, data availability, and interpretability, the initial economic development level is represented by the GDP of each city in the initial year (GDP), capital is represented by the proportion of fixed-asset investment to GDP (fix), the labor force is represented by the proportion of the total population excluding the employed population engaged in agriculture, forestry, animal husbandry and fishery (lab), economic openness is represented by the proportion of foreign direct investment to GDP (fdi), the quality of public services is represented by the number of hospital beds per 10,000 people (ame), the urbanization level is characterized by the urbanization rate (urban), and human capital is represented by the proportion of the population with high school education or above to the total population. Logarithmic processing is adopted for the initial economic development level to ensure data stability and elasticity of regression coefficients.

3.3.2. Spatial Econometric Model

Due to spatial constraints, panel data analysis omits spatial lags of the explained and explanatory variables. These can be added using the spatial regression model. In addition, spatial econometric methods can reduce the potential impact of missing variables in empirical models to a certain extent, especially with the spatial lag model used below, also known as Spatial Autoregression Model (SAR). The specific model settings are as follows [51]:

$$\triangle GDP_{it} = \alpha + p\sum_{j=1}^{n} w_{ij} \triangle GDP_{jt} + \beta X_{it} + \varnothing \sum_{j=1}^{n} w_{ij} X_{jt} + u_i + v_t + \varepsilon_{it} \quad (3)$$

where i and j represent different cities, t represents different times, ΔGDP_{it} is the GDP growth rate of city i in a period t, α is the intercept term of the model, p is the spatial lag coefficient of the explained variable, w_{ij} is the spatial weight matrix, according to the distance between each two cities, ΔGDP_{jt} is the GDP growth rate of city j in time period t, Φ is the spatial lag coefficient of the explanatory variable ($\Phi = 0$ in the spatial lag model), n is the number of cities, β is the estimated coefficient of the explanatory variable, X_{it} and X_{jt} represent all explanatory variables including inv_{it}, and u_i is the spatial effect, v_t is the time effect, and ε_{it} is the spatial error term that obeys an independent distribution.

4. Results

4.1. Spatial Feature Analysis

By linking the GDP growth rates of all cities in the YRD with the administrative data, we can see the spatial distribution characteristics (Figure 3). Overall, the spatial differences in the GDP growth rates of cities in the YRD region in different periods are significant. From the perspective of the four periods, the average annual GDP growth rate of cities such as Hefei, Wuhu, and Ma'anshan in Anhui Province, Nantong in Jiangsu, and Hangzhou in Zhejiang was above 10%. From 2000 to 2010, the average GDP growth rate of cities in the YRD region exceeded 15%, showing an increasing trend. The growth rate started to slow after 2010 to around 10% during 2015–2020. From 2005 to 2010, the GDP of each city in the YRD region reached the fastest growth rate, with an average of over 17%. From the perspective of spatial distribution, the spatial pattern of urban economic growth in the YRD region shows an outward trend. In the early stage, cities with relatively fast growth rates were mainly concentrated in the core area formed by 16 cities including Shanghai. After 2010, the economic growth rate of northern Anhui cities, northern Jiangsu cities, and southern Zhejiang cities began to accelerate and entered a stage of rapid development. Specifically, from 2000 to 2005, the GDP growth rate of cities in southern Jiangsu, northern Zhejiang, and surrounding cities of Hefei was relatively high, especially in Ma'anshan, Hefei, Suzhou, Tongling, etc. From 2005 to 2010, the GDP of cities around Hefei, Lianyungang, and Suqian grew rapidly. After 2010, the GDP growth rate of cities in the YRD slowed down. The GDP of Hefei and Wuhu grew faster from 2010 to 2015. After 2015, cities in northern Anhui such as Fuyang and Chuzhou experienced rapid GDP growth.

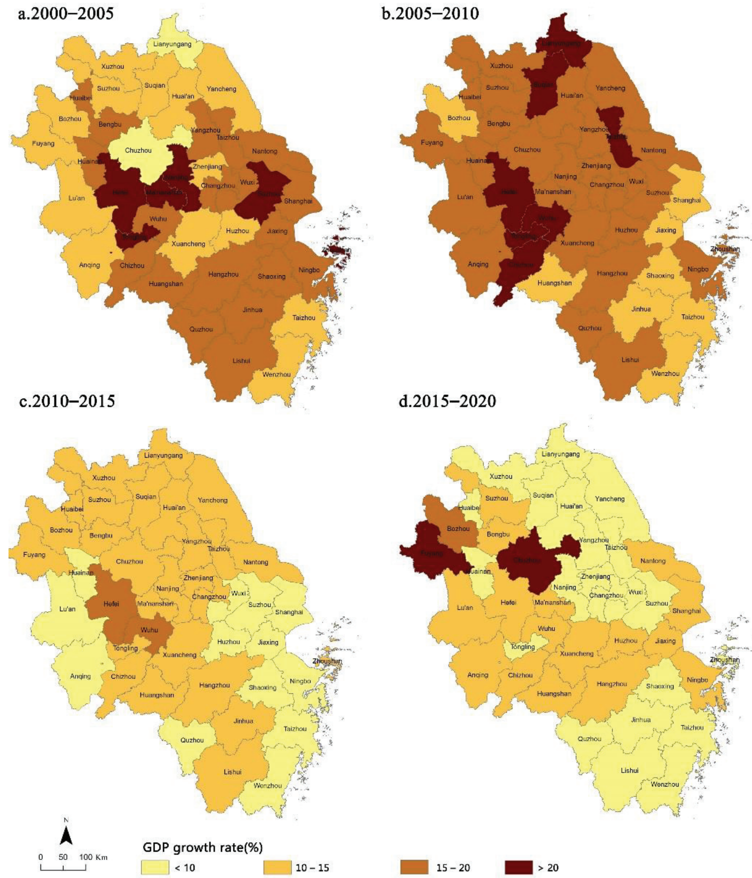

Figure 3. GDP growth rate of cities in the YRD during 2000–2020.

From the growth rate of Shanghai's investment in cities in the YRD (Figure 4), the areas affected by Shanghai's investment in the four periods were mainly concentrated in Hefei and Ma'anshan in Anhui, Lishui, and Jiaxing in Zhejiang, Nantong and Suqian in Jiangsu. The growth rate of Shanghai's investment over the years had exceeded 20%. From the perspective of time, the growth rate of Shanghai's investment in cities in the YRD from 2000 to 2020 showed a downward trend, from an average growth rate of about 40% in 2000–2005 to about 35% in 2015–2020. From the perspective of space, Shanghai's investment in cities in the YRD showed a state of outward diffusion. The growth rate of Shanghai's investment in surrounding cities was decreasing. On the contrary, the investment quota of other cities received outside the surrounding cities was gradually increasing. This may be related to the industrial transformation and upgrading as well as the economic radiation in the YRD region. With the acceleration of the integration process, other cities except the core area began to be affected by the radiation of Shanghai. Specifically, Shanghai's investment in other cities increased rapidly from 2000 to 2005, and then began to slow down. Taking a longitudinal perspective, because Shanghai had a solid investment foundation in the core cities of the YRD, a large amount of investment had been completed from the reform and opening-up to 2000, so the growth rate was relatively slow; alternatively, for the cities in northern Anhui and northern Zhejiang, the investment of Shanghai was not large, but had grown rapidly over the years.

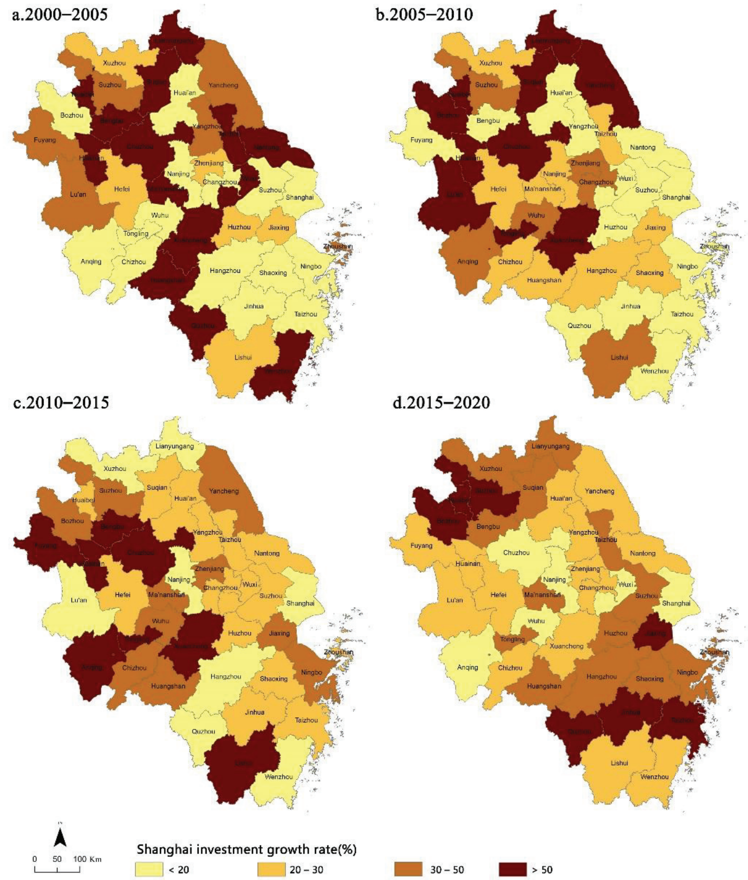

Figure 4. Shanghai's investment growth rate in cities in the YRD from 2000 to 2020.

Figure 5 presents the spatial characteristics of the investment growth rate of the cities in the YRD. The areas with rapid investment growth in the YRD cities in the four periods were mainly concentrated in Hefei, Ma'anshan, and Wuhu in Anhui Province, Nantong and Suqian in Jiangsu Province, and Huzhou in Zhejiang Province. The growth rate of investment in cities in the YRD had exceeded 20% over the years. From the perspective of different periods, the growth rate of investment within the YRD region had slowed down from 2000 to 2015, from 30% in 2000–2005 to 27% in 2010–2015. The growth started after 2015, and the average growth rate in 2015–2020 was 31%, which exceeded the growth rate in the period of 2000 to 2005. This may be related to the strengthening of links between cities in the YRD region and the increase in investment intensity after 2015. Overall, the growth rate of urban investment in the YRD region turned from north to south. Since 2000, cities in the YRD with rapid investment growth were mainly in Jiangsu Province and Anhui Province, including Nantong, Huainan, Fuyang, and Suqian during 2000–2005, and Chizhou Bozhou and Chuzhou during 2005–2010. Since 2010, cities in Zhejiang Province had been greatly affected by investment in the YRD region, represented by Zhoushan, Hangzhou, and Taizhou, and the growth rate of investment quotas in cities in the YRD had begun to increase.

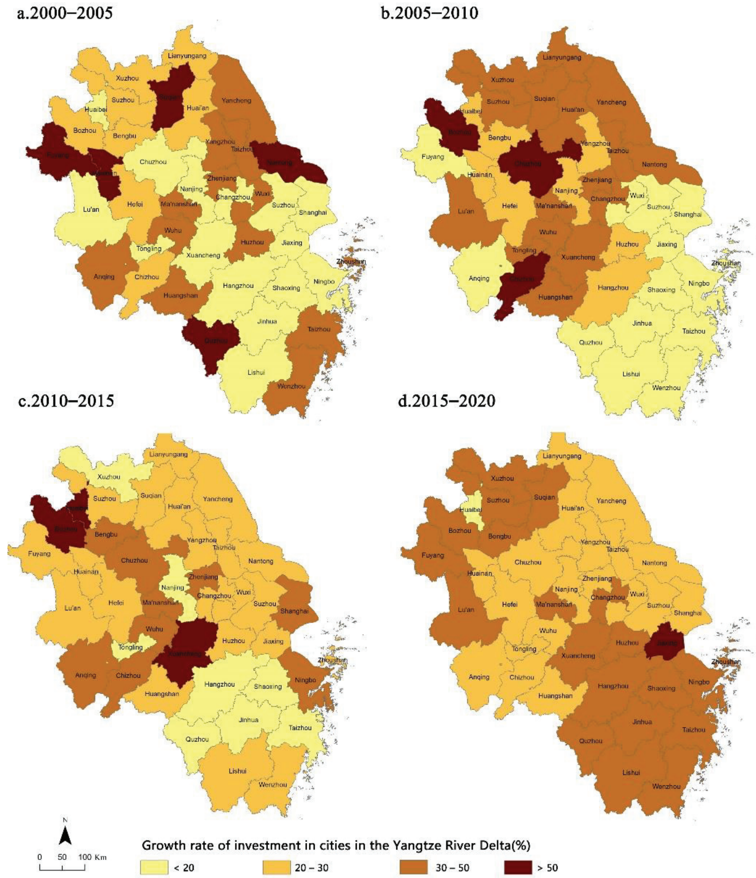

Figure 5. The investment growth rate of cities in the YRD during 2000–2020.

Figure 6 presents the investment growth rates of other cities across the country over the years. The regions with rapid investment growth in the four periods were mainly Hefei, Wuhu, and Ma'anshan in Anhui, Huai'an and Yancheng in Jiangsu, and Huzhou and Jiaxing in Zhejiang Province. From the perspective of different periods, the growth rate of investment from other cities in the country to cities in the YRD region had shown a continuous upward trend, from about 28% in 2000–2005 to about 40% in 2015–2020, which means that the investment intensity of other cities in the country in the YRD region was increasing, which was also closely related to the continuous improvement of the economic vitality of the YRD region. On the whole, the growth rate of investment in other cities across the country turned from northwest to southeast. From 2000 to 2005, the areas with higher growth rates were concentrated in Ma'anshan, Chuzhou, and other cities in the northwest of the YRD region. From 2015 to 2020, Hangzhou, Jiaxing, Ningbo, and other cities had higher investment growth rates. Specifically, before 2010, some cities in southern Zhejiang and northern Anhui, e.g., Maanshan, Chuzhou, Lishui, and Quzhou, received higher investment growth rates from other cities across the country. From 2010 to 2015, most cities in Anhui, e.g., Xuancheng, Huainan, and Wuhu, had a larger increase in investment from other cities across the country. After 2015, other cities across the country have increased the investment in cities to Zhejiang Province, including Hangzhou, Jiaxing, Zhoushan, etc.

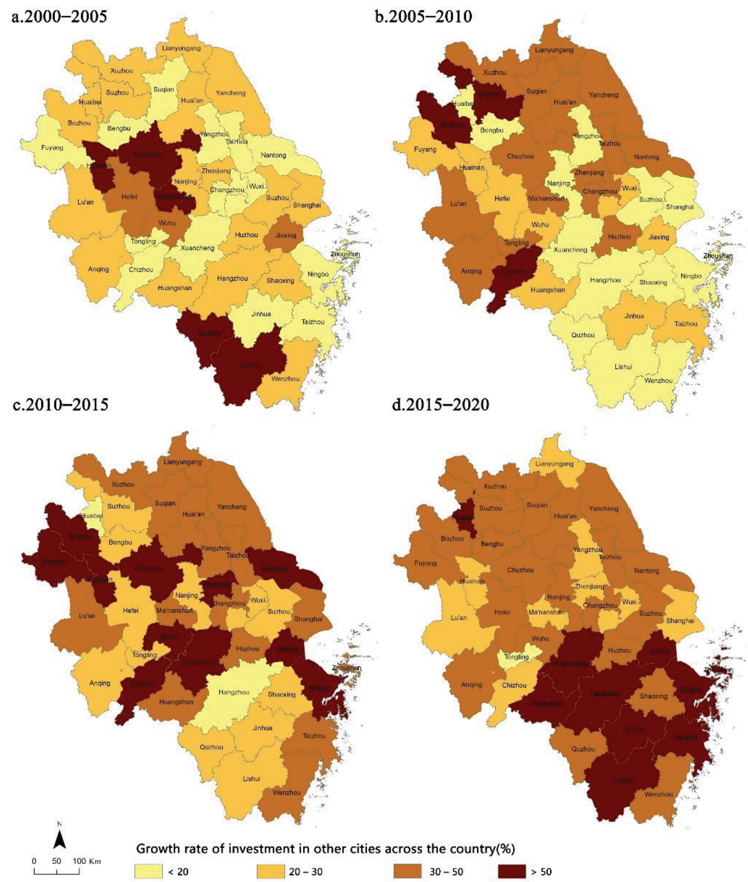

Figure 6. The investment growth rate from other cities across the country during 2000–2020.

4.2. Benchmark Regression Model Results

According to the set indicators, the relevant variables were brought into the formula, and then the panel model was used for estimation and calculation. The test found no multicollinearity and heteroscedasticity problems. A Hausman test was used to choose between a random-effect and fixed-effect model. The probability of the Hausman test was smaller than expected, so the fixed-effect model was adopted. Model (1) in Table 2 was used to estimate the impact on urban economic growth when only adding investment growth in cities in the YRD. Model (2) was used to estimate the impact on urban economic growth when only adding investment growth in other cities across the country. Model (3) was used to estimate the impact on urban economic growth when only adding Shanghai's investment growth. Models (4) to (6) combine investment growth in cities in the YRD, investment growth in other cities across the country, and Shanghai's investment growth to estimate the impact of different combinations on urban economic growth. Model (7) comprehensively considers the investment growth of cities in the YRD, the investment growth of other cities in the country, and Shanghai's investment growth, and estimates the impact on urban economic growth.

Table 2. The fixed-effect model of investment growth on urban economic growth.

Variables	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
Investment within the YRD	0.048 ** (2.07)	-	-	0.057 ** (2.05)	-	0.039 * (1.66)	0.053 * (1.95)
Investment to the YRD cities by other cities across the country	-	0.034 ** (2.36)	-	-	0.034 ** (2.27)	0.029 ** (2.01)	0.032 ** (2.18)
Investment to the YRD cities by the core city (Shanghai)	-	-	0.006 (0.59)	−0.006 (−0.57)	−0.001 (−0.06)	-	−0.011 (−1.03)
Initial economic development level	−0.063 *** (−4.66)	−0.064 *** (−4.73)	−0.070 *** (−5.23)	−0.062 *** (−4.54)	−0.063 *** (−4.70)	−0.059 *** (−4.32)	−0.057 *** (−4.10)
Urbanization level	0.012 (0.31)	−0.002 (−0.04)	0.021 (0.53)	0.012 (0.30)	−0.002 (−0.04)	−0.007 (−0.17)	−0.009 (−0.23)
Labor force	0.654 *** (2.94)	0.576 ** (2.61)	0.622 *** (2.75)	0.651 *** (2.91)	0.575 ** (2.58)	0.615 *** (2.79)	0.604 *** (2.74)
Proportion of foreign direct investment to GDP	0.520 *** (2.79)	0.532 *** (2.86)	0.494 ** (2.61)	0.515 *** (2.75)	0.531 *** (2.84)	0.555 *** (3.00)	0.548 *** (2.97)
Proportion of fixed-asset investment to GDP	0.044 ** (2.11)	0.043 ** (2.10)	0.050 ** (2.35)	0.042 * (1.96)	0.043 ** (2.06)	0.040 * (1.96)	0.036 * (1.71)
Quality of public services	−0.000 (−0.19)	−0.000 (−0.01)	0.000 (0.37)	−0.000 (−0.28)	−0.000 (−0.01)	−0.000 (−0.41)	−0.000 (−0.59)
Human capital	0.041 (0.39)	0.049 (0.47)	0.052 (0.49)	0.041 (0.39)	0.049 (0.47)	0.039 (0.38)	0.039 (0.38)
Constant	0.453 * (1.75)	0.534 ** (2.14)	0.585 ** (2.30)	0.443 * (1.70)	0.535 ** (2.13)	0.425 (1.66)	0.405 (1.57)
N	164	164	164	164	164	164	164
R^2	0.62	0.63	0.61	0.62	0.63	0.64	0.64

Notes: Robust standard errors are shown in parentheses; ***, **, * represent $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.

In general, after controlling other influencing factors, the growth of investment in cities both outside and within the urban agglomeration had a significant effect on economic growth. The faster the investment grows within and outside the urban agglomeration, the faster the economy grows. However, the coefficient of the investment growth rate within the urban agglomeration was larger, and compared with that outside the urban agglomeration, the promotion effect on urban economic growth was more obvious. In addition, the growth of urban investment of the core city (Shanghai) in the urban agglomeration did not significantly improve urban economic growth.

Specifically, the core explanatory variable of model (1) was the growth of urban investment within the urban agglomeration, and the result was positive and significant, indicating that, in general, the investment growth within the YRD region had driven the urban economic growth. The faster the investment grows within the urban agglomeration, the faster the urban economy grows. Models (2) and (3) test the investment growth in other cities across the country and the investment growth of Shanghai separately. The results showed that the investment growth variable in other cities across the country was significant, while the investment growth variable in Shanghai was not significant, and did not affect other variables significantly. The results showed that the investment growth in other cities outside the urban agglomeration had a significant impact on the urban economic growth, but the investment growth of the core city did not have a significant impact on the urban economic growth. Model (4) combined the investment growth of other cities in the country and the investment growth of Shanghai to test joint effects; Model (5) combined the investment growth of the YRD cities and the investment growth of Shanghai to test joint effects. The results showed that the investment growth of the YRD cities and the investment growth of other cities in the country were still positive and significant, and the variable of Shanghai's investment growth was not significant, which further indicates that the investment growth of the core city cannot significantly improve economic growth in urban agglomerations. Model (6) was used to test the combined effect of the investment growth of other cities in the country and the investment growth within the YRD region. The results showed that both variables were positive and significant, with coefficients of 0.039 and 0.029, respectively, and the investment growth coefficient of the YRD cities was bigger than that of other cities in the country, indicating that the growth of internal investment in the YRD region had a bigger effect on urban economic growth, compared with the effect of investment growth in other cities across the country. Model (7) showed that when considering the growth of internal investment in the urban agglomeration, external investment, and investment growth of the core city at the same time, the driving function of internal investment growth in the YRD region and investment growth in other cities across the country was verified again, and the former exerted a more significant impact than the latter, and the coefficients of 0.053 and 0.032, respectively, passed the significance test at the level of 10% and 5%. In Model (1), R^2 was improved to a certain extent. At this time, if the investment growth of cities in the YRD increases by 10%, the urban economy will grow by 0.53%; if the investment growth of other cities across the country increases by 10%, the urban economy will grow by 0.32%.

From the above analysis, it can be seen that the investment growth within the YRD region had a significant positive effect on urban economic growth, and the effect was greater than the investment growth of cities outside the urban agglomeration, which also showed that increasing urban connections and industries within the urban agglomeration investment could significantly drive urban economic growth. In addition to investment growth, the following table also measured the impact of other factors on urban economic growth. The initial economic development level was significant in the model, passed the significance test at the level of 1%, indicating that cities with lower initial economic development levels had faster economic growth, and there was a conditional convergence. The estimated coefficient of labor force was also significantly positive, indicating that the improvement of the labor factor had a greater contribution to the urban economic growth. Foreign direct investment not only brought employment opportunities to cities, but also facilitated technology spillovers, so it had a positive effect on urban economic growth. Fixed asset investment accounts for a relatively high proportion of GDP, which could drive the construction of various urban infrastructure and significantly promote economic growth. Other variables such as urbanization rate, public service quality, and human capital did not exert a significant impact on economic growth.

4.3. Robustness Test Results

The interaction between cities in the YRD region would have a certain spatial autocorrelation, so this paper adopted a spatial panel model for further analysis. On the one hand, the spatial panel model could solve the estimation bias caused by the fixed-effect model ignoring spatial correlation and omitting spatially correlated variables to a certain extent. On the other hand, the estimation results of the spatial panel model can also be regarded as the robustness of the previous two models' test to verify whether the model estimation results and conclusions drawn in this paper were robust and reliable. By calculating the global Moran's index of the four-period data and testing the Moran's index, the paper found that the Moran's index of the economic growth rate variable was positive in 2005–2010, 2010–2015, and 2015–2020, and the Moran's index in 2005–2010 and 2010–2015 strongly rejected the null hypothesis of "no spatial autocorrelation", which showed that there was spatial autocorrelation in the economic growth rate in a certain period. Therefore, the robustness test of the models in Table 2 was carried out, and the results of the SAR model were found to be better after comparison, so this study adopted the results of the SAR model. Similarly, before the spatial regression analysis, it was necessary to perform the Hausman test to decide on the selected panel regression model. The Hausman test showed that a fixed-effects spatial error model should be used. Using Stata software, the spatial error model regression was performed on the data, and the results are shown in the following table.

Compared with Table 2, Table 3 showed that the results of the spatial econometric analysis were basically unchanged. The investment growth of cities in the YRD and across the country were still positive and significant to the GDP growth rate, and the coefficients 0.053 and 0.032, respectively, passed the significance test at the level of 5% and 1%, and the positive effect of investment growth of cities in the YRD was greater than the that of cities across the country. The initial economic level was negative and significant, and variables such as the proportion of labor force, the proportion of foreign direct investment, and the proportion of fixed-asset investment still had a positive and significant effect. From the above results, even considering the spatial interdependence between different cities, the growth of investment within the YRD region played a relatively stable role in the long-term economic growth process of a city.

Table 3. The spatial econometric results of GDP growth model.

Variables	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
Investment within the YRD	0.038 ** (2.03)	-	-	0.048 ** (2.17)	-	0.029 * (1.55)	0.044 ** (2.06)
Investment to the YRD cities by other cities across the country	-	0.031 *** (2.81)	-	-	0.033 *** (2.82)	0.028 ** (2.47)	0.031 *** (2.73)
Investment to the YRD cities by the core city (Shanghai)	-	-	0.003 (0.35)	−0.007 (−0.83)	−0.003 (−0.44)	-	−0.012 (−1.41)
Initial economic development level	−0.061 *** (−5.63)	−0.060 *** (−5.62)	−0.066 *** (−6.21)	−0.060 *** (−5.48)	−0.059 *** (−5.60)	−0.056 *** (−5.24)	−0.054 *** (−4.97)
Urbanization level	0.059 * (1.78)	0.047 (1.40)	0.069 ** (2.08)	0.059 * (1.79)	0.047 (1.41)	0.041 (1.22)	0.039 (1.17)
Labor force	0.677 *** (3.83)	0.611 *** (3.51)	0.649 *** (3.64)	0.673 *** (3.82)	0.604 *** (3.46)	0.639 *** (3.67)	0.627 *** (3.62)
Proportion of foreign direct investment to GDP	0.461 *** (3.11)	0.475 *** (3.24)	0.435 *** (2.90)	0.454 *** (3.06)	0.470 *** (3.20)	0.495 *** (3.38)	0.487 *** (3.34)
Proportion of fixed-asset investment to GDP	0.048 *** (2.88)	0.047 *** (2.86)	0.052 *** (3.12)	0.045 *** (2.69)	0.046 *** (2.78)	0.044 *** (2.72)	0.039 ** (2.40)
Quality of public services	0.000 (0.43)	0.000 (0.59)	0.000 (1.04)	0.000 (0.31)	0.000 (0.58)	0.000 (0.17)	−0.000 (−0.06)
Human capital	0.069 (0.84)	0.076 (0.93)	0.080 (0.96)	0.070 (0.84)	0.078 (0.95)	0.067 (0.83)	0.068 (0.84)
ρ	0.441 *** (3.97)	0.461 *** (4.25)	0.465 *** (4.21)	0.444 *** (4.00)	0.465 *** (4.28)	0.441 *** (4.01)	0.446 *** (4.08)

Notes: Robust standard errors are shown in parentheses; ***, **, * represent $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.

5. Conclusions and Discussion

5.1. Conclusions

This paper discussed the impact and role of agglomeration externalities and network externalities on urban development. Taking 41 cities in the YRD region as the research object, it analyzed the spatial pattern of GDP growth rate of urban agglomeration cities, Shanghai's investment growth rate, the investment growth rate of cities in the YRD, and the investment growth rate in other cities across the country, and examined the impact of both network externalities and agglomeration externalities on urban economic development at the scale of urban agglomerations. The results of this study show that:

1. From 2000 to 2010, the average GDP growth rate of cities in the YRD region showed a rapid growth trend, but it began to slow down after 2010. The economic growth of cities in the YRD region presents an outward spatial pattern. In the early stage, it was mainly concentrated in the core area formed by 16 cities including Shanghai. In 2010, the economic growth rate of cities in northern Anhui, northern Jiangsu, and southern Zhejiang began to accelerate, entering the stage of rapid development.
2. From 2000 to 2020, the growth rate of Shanghai's investment to the cities in the YRD showed a downward trend and an outward spatial diffusion. The growth rate of Shanghai's investment to its surrounding cities began to decrease. On the contrary, the investment quota from Shanghai outside the surrounding area had gradually increased. The growth rate of investment within the YRD region showed a slowing trend from 2000 to 2015, and increased after 2015, showing a spatial distribution from

northwest to southeast. From 2000 to 2020, the growth rate of investment from other cities in the country to cities in the YRD region showed a continuous upward trend, and spatially formed a distribution characteristic from northwest to southeast.

3. From the perspective of long-term economic growth, the growth of internal investment in the YRD region and the growth of investment in other cities across the country could promote urban economic growth, and the growth of internal investment in the YRD region had a greater role in promoting economic growth than that of other cities across the country. Both “agglomeration externalities” and “network externalities” at the urban agglomeration scale promoted urban economic growth, but the role of “agglomeration externalities” within urban agglomerations were more obvious. The possible explanation was that a relatively complete regional division of labor network had basically been formed within the YRD, and the investment growth of other cities outside the urban agglomeration had a less obvious promoting effect on the urban economic growth than the investment growth within the urban agglomeration. The side confirmed that promoting the regional integration process of the YRD could promote the economic development of cities within the urban agglomeration. This provided economic scientific support for the integrated development strategy of the YRD region. It was necessary to continue to deepen the process of internal integration of the urban agglomeration. Through the mutual radiation function between cities, the agglomeration effect within the urban agglomeration could be exerted, and the economic growth of large, medium, and small cities within urban agglomerations could be promoted.
4. The investment of the core city, Shanghai, did not play a significant role in the long-term economic growth of other cities in the region. Regardless of whether the impact of the investment of the core city or that of other cities outside the urban agglomeration on urban economic growth were considered alone, and whether the role of several factors was collectively considered at the same time, the results only found that promoting effect of investment growth within the urban agglomeration and that of other cities outside the urban agglomeration on urban economic growth. The possible explanation for this was that the core city of Shanghai had a promotion effect on the economic radiation to its surrounding cities or cities within a certain distance, but from the YRD region as a whole, the economic radiation of Shanghai was limited.

Different from analyzing the impact of network externalities and agglomeration externalities at the urban scale, this paper further extends the urban scale analysis to the urban agglomeration scale analysis and tests the YRD region as an empirical object. The research results showed that both “network externalities” and “agglomeration externalities” at the scale of urban agglomerations could significantly promote urban economic growth, and the promoting role of urban investment within urban agglomerations was more obvious, which provided scientific support for the integrated development of the YRD region.

5.2. Discussion

With the continuous development of economic globalization and regional integration, urban agglomerations have become important spatial and regional units for countries to participate in global competition and international division of labor, and have profoundly affected the new political and economic pattern over the world. From the research results of the article, strengthening inter-city connections within urban agglomerations can promote urban economic development and help urban agglomerations become regional growth centers and innovation centers. In the future, in the process of regional integration in the YRD, it is necessary to strengthen the economic and social ties between the cities in the urban agglomeration, and improve the level of integrated development in the fields of deep industrial co-ordination, cultural system identification, infrastructure interconnection, ecological environmental protection, and public service sharing, and realize higher-quality integrated development of urban agglomerations.

Overall, this paper measures the impact of network externalities and agglomeration externalities on urban development at the scale of urban agglomeration, but further improvement could be conducted: (1) To expand the spatial dimension of the research samples. This paper selects the YRD region as the case, and the applicability to other urban agglomerations needs to be expanded. In the future, it is necessary to conduct extended research on a larger spatial scale to make up and improve the conclusions of this paper. (2) In this paper, only 41 prefecture-level cities within the urban agglomeration are selected for research. In the future, it will be considered at the county level. The results at the district and county levels need to be further verified. (3) This paper selects 2000–2020 as the research period, which may produce heterogeneous results upon different period selection. In the future, it is necessary to extend the research on longer time periods. (4) Since the YRD region is closely connected with other regions and cities in the world, the follow-up will obtain and use international investment data, incorporate international investment variables, and analyze its impact on urban economic development.

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Article

Multi-Dimensional Urbanization Coordinated Evolution Process and Ecological Risk Response in the Yangtze River Delta

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Abstract: The dislocated development of population, land, and economy will disturb the urban system, cause ecological risk problems, and ultimately affect regional habitat and quality development. Based on social statistics and nighttime lighting data from 2000 to 2018, we used mathematical statistics and spatial analysis methods to analyze the change process of urbanization's coupling coordination degree and ecological risk response pattern in the Yangtze River Delta. Results show that: ① From 2000 to 2018, the coupling coordination degree of urbanization in the Yangtze River Delta increased, with high values in Suzhou-Wuxi-Changzhou, Shanghai, Nanjing and Hangzhou regions. ② The ecological risk in the Yangtze River Delta weakened, and the vulnerability and disturbance of landscape components together constitute the spatial differentiation pattern of regional ecological risk, which presented homogeneous aggregation and heterogeneous isolation. ③ The overall ecological stress of urbanization in the Yangtze River Delta decreased. ④ The population aggregation degree, socio-economic development level and built-up area expansion trend contributed to the spatiotemporal differentiation of urbanization's ecological risks through the synergistic effects of factor concentration and diffusion, population quality cultivation and improvement, technological progress and dispersion, industrial structure adjustment and upgrading. This study can provide a reference for regional urbanization to deal with ecological risks reasonably and achieve high-quality development.

Keywords: urbanization; coordinated development; spatial-temporal evolution; ecological risk; Yangtze River Delta

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1. Introduction

Urbanization is an important symbol of the steady development of society, economy and culture and is a necessary stage of historical development in a country or region [1]. Nevertheless, countries such as the United States, the United Kingdom, Japan, Korea, Brazil, India, and Pakistan all suffer from urbanization threatening the ecological environment during their initial and rapid development periods. Ecological imbalance, environmental contamination, resource depletion, and other ecological risks are negatively impacted by urbanization [2–4]. Furthermore, urbanization and industrialization patterns in the wider region in which the study area is sited—that is, east Asia and China—differ from that of the old industrial countries of Europe and North America. China has experienced the most extensive and fastest urbanization process in the world. Due to the compression of space and time, quite a few concentrated conflicts have emerged. Specifically, excessive attention has been paid to economic urbanization leads and to land urbanization ahead of population urbanization. The dislocation of these three components in China has generated more ecological and environmental issues than any other country or region [5], which has, in turn, attracted the attention of widespread international communities.

The studies show that the ecological risk problem in areas with low-level urbanization is relatively simple. The higher urbanization level means more substantial disturbances by human behavior, which has a more profound influence on urban space, population, and industrial structure, generating a wide range of influence and a high frequency of ecological risks [6,7]. Unfortunately, no unified standard exists for evaluating urbanization level, only some single index (i.e., urban population proportion, urban land proportion, etc.) and compound index evaluation methods [7,8]. Since the single index method can only reflect a specific aspect of urbanization quantitatively, the composite index method that comprehensively evaluates the overall development quality is more desirable. Considering that the development mode of urbanization also profoundly impacts the ecological environment [9–11], which development model is more conducive to mitigating ecological risks has been a global problem and strategic issue.

The primary attributes of urbanization should include complexity, diversity, and heterogeneity [12]. However, most previous studies have adopted physical expansion rather than an original improvement to simplify the complexity of urban development, including urban expansion, fragmentation and inefficiency of land use, and spatial configurations that disrupt landscape patterns, thereby increasing habitat sensitivity and vulnerability [13]. There is also an insufficient awareness of diversity. The GDP-only model of urban development violates the law of geographical differentiation, resulting in insufficient inclusion and feedback of various material and energy flows, accumulation of potential impacts, risk receptors, and explosive risks over time, all of which complicate the assessment and management process [14]. Moreover, because we ignore heterogeneity, population growth, economic development, and urban spatial expansion fail to cooperate in urbanization [15]. This phenomenon directly affects the ecosystem's resistance, recovery, and stability, generating chain risk events in the soil, atmosphere, and biosphere. Therefore, urbanization is a multi-dimensional process of spatial change [16,17], and it refers to the process of population agglomeration in cities and towns, the expansion of the urban scale and the resulting economic and social changes, including economic urbanization, population urbanization, and land urbanization [18]. Scholars usually understand this intrinsic connection as urbanization. Its root and core lie in the decline of the proportion of the rural population and the increase of the proportion of the urban population. The industrial structure shifts from an agricultural economy to an industrial economy with the service industry as the economic pillar, driven by the evolution of social structures from rural to urban societies. With the changes in population and economic society in geographical space, land urbanization is the bearer of the urbanization system [19]. The subsystems of economic urbanization, population urbanization and land urbanization complement each other, which is called collaborative urbanization [20]. Only a coordinated development of population, economy, and land urbanization can control and prevent the ecological risks [18,21].

China faces severe ecological and environmental problems, especially in the eastern urban agglomerations. Therefore, it is crucial to explore the conceptual content and evaluation methods of urbanization's ecological risks for taking adequate early warning and remedial measures. The U.S. Environmental Protection Agency introduced the concept of ecological risk assessment in the 1980s for environmental management objectives. Nowadays, ecological risk assessment has experienced a development process from environmental risk to the ecological risk and then to regional ecological risk assessment. The risk sources have expanded from single to multiple risk sources, and the evaluation scope has expanded from a local to a regional landscape level [22]. Research on urbanization's ecological risk mainly involves the following aspects: (1) conceptual analysis of urbanization's ecological risk [23,24]; (2) judgement of urbanization's ecological risk level [25,26]; and (3) regulation and control of urbanization's ecological risk [27–29]. Generally speaking, urbanization's ecological risk is the degree and possibility that urban development and construction and human activities will bring adverse changes to ecological elements, processes, and ecosystem services or threats to human health. The methodology system of urbanization's ecological risk constructed from different perspectives and methods is put forward, which mainly includes three major types. The first is the construction of comprehensive indices or model simulations from risk sources, habitats and ecological receptors in terms of physical damage, such as the biological effect evaluation index method [30,31], the relative risk method [32], the exposure–response method [33], fuzzy mathematics, and grey system [34]. The second is the landscape ecological risk index, which is constructed from the landscape's vulnerability, disturbance, and resilience based on a landscape analysis perspective [35,36]. The third is to use GIS and RS technology to obtain risk information and combine Ripley's k function with geostatistics from a spatial perspective [37].

In summary, the academic community has paid attention to the extent and impact of the ecological risks of urbanization from different perspectives. Nonetheless, there are two main shortcomings. First, previous studies have stayed on the correlation between urbanization level and ecological risks, focusing on the spatial location, distribution pattern and quantitative correlation evaluation between urbanization level and ecological risks in a specific cross-sectional time. Some scholars have studied the coupling trend, effect and mechanism of the two, but research on the ecological risk caused by different population allocations, industry and land in cities and towns is weak. The synergy of population gathering, industrialization, and land use are more in line with the diversified requirements of cities and habitats. Secondly, urbanization ecological risk assessment mostly takes administrative units as the data carrier because Chinese socioeconomic data are cascaded by administrative units. However, many ecological risks are difficult to measure by socioeconomic data, making it difficult to describe the spatial patterns of urbanization ecological risks. Therefore, this study could supplement the theoretical perspective of urbanization ecological risks and refine the scale of related studies.

The Yangtze River Delta is one of the regions with the best urbanization foundations in China. With outstanding location advantages, superior natural endowments and comprehensive solid strength, it is one of the six major urban agglomerations in the world. The Outline of the Yangtze River Delta Regional Integrated Development Plan issued in 2019 elevates the integrated development of the Delta to a national strategy. However, the Yangtze River Delta faces a fierce contradiction between territorial space development and ecological protection, which threatens the quality and sustainability of regional urbanization development. Therefore, exploring coordinated regional urbanization and ecological risk response in the Yangtze River Delta is crucial in promoting ecological civilization construction. To fill the gaps above, taking the Yangtze River Delta as an example, this study investigates the coordinated evolution process of urbanization and its ecological risk response in the Delta based on a five km * five km raster scale from 2000 to 2018 with the help of downscaling analysis, coupling coordination, an ecological risk evaluation model, and a trend analysis. This study aims: (1) to scientifically recognize the distribution characteristics and laws of ecological risk under the role of collaborative urbanization development; and (2) to attempt to complement the study on the spatiotemporal correlation between the two at the raster scale. This study is expected to guide the implementation of new urbanization and regional integration policies in the relevant regions and to provide scientific guidance for mitigating and controlling ecological risks.

2. Coupling Mechanism of Urbanization Coordination and Ecological Risk

2.1. Technical Roadmap of This Research

This study intends to portray the combined state of multidimensional urbanization quantitatively, to measure the spatial and temporal distribution characteristics of ecological risks based on the goal of high-quality regional development, and to refine the driving mechanism of ecological risks of regional urbanization through an analysis of the interaction relationship between multidimensional urbanization and ecological risks. As a result, we try to provide a reference for regional development practice (Figure 1). The steps of the study are as follows: (1) Quantitative measurement of multidimensional urbanization.

Based on the perspective of a balanced coordination of population urbanization, economic urbanization, and land urbanization, the paper spatially expresses the population density, economic density and spatial extent of urbanization, respectively, in the Yangtze River Delta region from 2000 to 2018 with the help of downscaling models and a nighttime light database. (2) Ecological risk measurement. In this section, the paper constructs risk plots and uses a landscape pattern index to evaluate regional ecological risk change patterns. (3) Multidimensional urbanization and ecological risk response patterns. Based on the analysis of the change characteristics of multidimensional urbanization and ecological risk, we combine the changes in population urbanization, economic urbanization, and land urbanization elements in the Yangtze River Delta from 2000 to 2018 and comprehensively refine the driving mechanism of urbanization's ecological risk in the Delta.

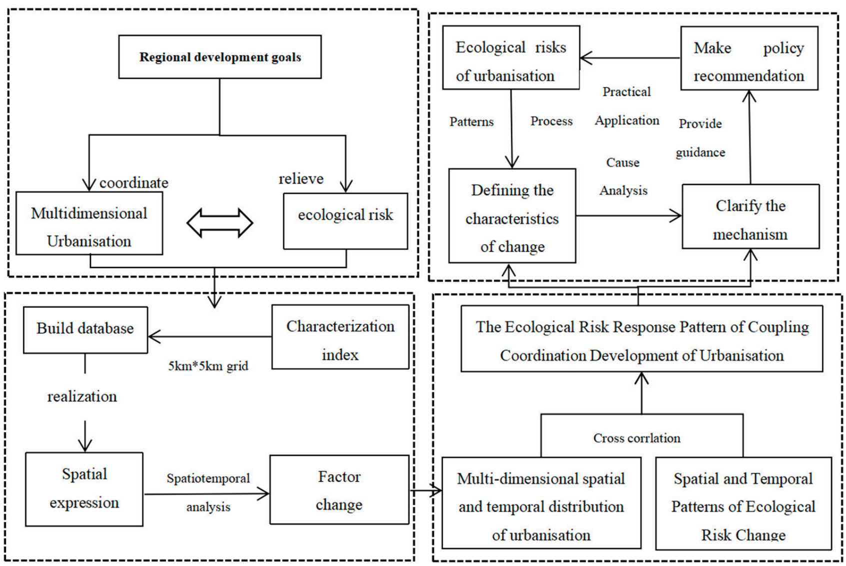

Figure 1. The research technical route.

2.2. Interaction of Urbanization and Ecological Risk

Population growth, economic development, and spatial expansion in urbanization could induce ecological risks. ① Population urbanization is mainly the migration of the agricultural population to the non-agricultural population. With the rapid increase in population density and consumption level [38], the large population in urban centers brings challenges to living, commuting, etc. These pressures have to be alleviated by outward expansion and increased production and living pollutants. Meanwhile, the growing consumer demand poses more significant challenges to the supply capacity of water and land resources; if the disturbance force exceeds the natural system's carrying capacity, the ecosystem's elasticity will decline and collapse, eventually leading to an increase in ecological risk.

② Economic urbanization is mainly manifested in the level of industrialization and in the upgrading and adjustment of the industrial structure [39]. Among them, industrialization refers to transforming primary products into final products through one or more processing methods and is the main engine driving urbanization. On the one hand, the initial stage of industrialization is relatively rough and inefficient, and the pollution of waste gas, wastewater, and industrial solid waste generated during this process seriously threatens the atmosphere and the hydrosphere. On the other hand, in the middle and late stages of industrialization, ecological risks are reduced due to the improvement of production efficiency, the implementation of environmental regulations, the improvement of clean production technologies and the upgrading and adjustment of industrial structures, but due to the stress of long-term cyclic accumulation, the ecosystem still has hidden, long-term and uncertain risks [40,41].

③ Land urbanization is manifested in the change of urban landscape patterns and the expansion of the geographical expansion of built-up areas [42]. Land rent theory argues that people pursue economic growth in land ownership. Therefore, the early expansion of construction land mainly depends on the deprivation of many low-value-added cultivated lands and natural ecological land, resulting in a severe depletion of ecosystem services and a decline in ecosystem self-recovery and adaptative capacity. In addition, it is easier to maintain its stability for intensive, compact, and continuous landscapes. However, during this period, people's investment in construction is high. The intensity of urban sprawl tends to lead to a decline in the compactness of the landscape on the fringes of towns, scattered urban forms, fragmentation of each landscape component, and a sharp increase in ecological risks. In the middle and later stages of development, land use is developed by spatial governance and protection of territorial space, which can gradually improve the spatial structure, form, and interaction of towns and cities with the scale agglomeration effect of population and industry to reduce ecological risks.

Population, spatial, and economic urbanization, as a complicated system, are not affected individually but interfere with each other, resulting in co-frequency resonance or negative superposition according to the coupling and coordination of all three. Rapid population urbanization is the root and core driver of risks. In contrast, rapid industrialization is the engine and driving force to solve the demand for transportation, employment, housing, and consumption caused by rapid population urbanization. However, this industrialization also brings more severe and broader ecological risk threats. The mediating effect of land urbanization on population and economic population enhances ecological vulnerability, further deepening and consolidating ecological risks [18,21]. Therefore, the mandatory interaction between urbanization and ecological risks need to be studied from a synergistic perspective of population, economy, and space (Figure 2).

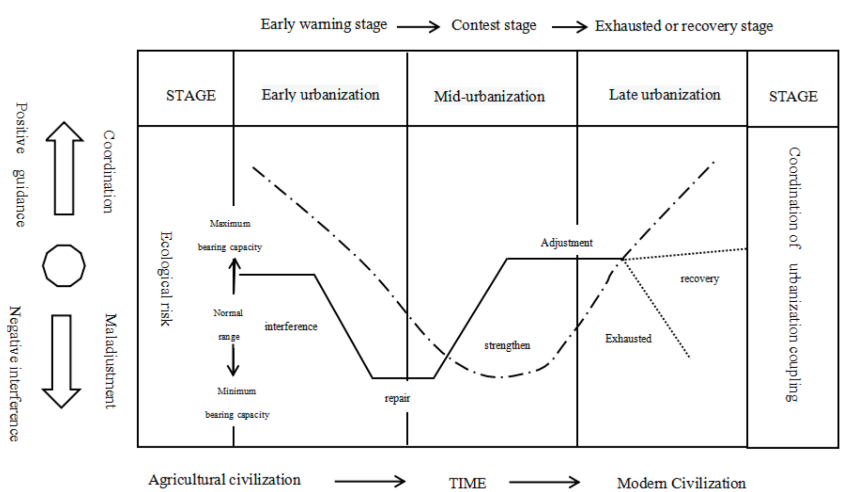

Figure 2. The interactive relationship between urbanization and ecological risk.

3. Materials and Methods

3.1. Study Area

The Yangtze River Delta is located on the eastern coast of China, with latitude 32°34′ N–29°20′ N and longitude 115°46′ E–123°25′ E. It includes the four provinces of Shanghai, Jiangsu, Zhejiang, and Anhui, with 41 cities and 358,000 square kilometers. It is at the intersection of the Yangtze River Economic Belt and the One Belt, One Road Initiative.

Although the strategic position of the Delta is vital, its national spatial development and ecological environment coercion problems are also prominent, and there is an urgent need to formulate appropriate management policies and congestion relief plans.

This study selects the Yangtze River Delta region as the research object, mainly based on three considerations. (1) Strong leadership and demonstration skills. The Yangtze River Delta is the region with the highest and fastest urbanization level in China, with an average annual urbanization growth rate of 9.2%, a large population inflow, and an average annual GDP growth rate of 15.7% [43]. The total economic output of the Yangtze River Delta region is close to 25% of the national total. The region is also at the forefront of China's high-tech industry development. (2) A larger threat of ecological risks. The natural ecosystem of the Yangtze River Delta has been disturbed by human activities, and the landscape pattern of the Delta has undergone significant changes. In the past 18 years, the cultivated land, grassland, and forest land have declined significantly, and the release area change rates were −8.76%, −2.61%, and −1.83%, respectively. Meanwhile, construction land showed a significant upward trend, the area change rate was as high as 293.41% (Table 1), the natural landscape continued to decline, and the artificial landscape continued to expand. Therefore, the United Nations Intergovernmental Panel on Climate Change has listed the Yangtze River Delta as an ecological risk hotspot [44]. (3) More significant natural spatial heterogeneity and socioeconomic development gradient. The natural environment in the Yangtze River Delta is significantly different, with diverse terrain and prominent and zonal topography. They were bounded by the Yangtze River and the famous Yangtze River Delta Plain to the north. The terrain is gentle and undulating, and the south is mountainous hills, such as the hilly mountains in southern Anhui and the hilly plains in southwestern Zhejiang, where the climate is divided by the line of the Huaihe-Subei irrigation canal and the transitional characteristics are a subtropical to warm temperate zone (Figure 3). There are apparent regional economic differences in the Yangtze River Delta, with Shanghai at the center and the development pattern of coastal river networks where the Suzhou-Wuxi-Changzhou city group, the Hangzhou-Jiaxing-Huzhou city group, the Nanjing metropolitan area, the Hefei metropolitan area, and the Ningbo metropolitan area are formed. Nevertheless, the development of the northern Anhui, the southwest Zhejiang, and the northern Jiangsu, which are on the outer edges of the circle, are still relatively lagging. The regional economic and social development stages are lagging, which is not conducive to regional integration and coordinated development.

Table 1. Changes in land use types in the Yangtze River Delta from 2000 to 2018.

Type / Year	2000		2005		2010		2015		2018	
	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)
Arable land	182,941.11	52.19	179,152.27	51.11	171,977.93	49.06	168,954.51	48.20	166,918.21	47.62
Forest land	100,643.55	28.71	100,349.82	28.63	99,665.73	28.43	99,519.75	28.39	98,805.10	28.19
Grassland	11,559.02	3.30	11,473.62	3.27	11,227.37	3.20	11,141.03	3.18	11,257.23	3.21
Water Area	24,431.04	6.97	24,825.26	7.08	25,588.71	7.30	25,717.68	7.34	25,531.47	7.28
Construction Land	30,918.76	8.82	34,697.26	9.90	41,876.91	11.95	45,019.11	12.84	47,803.06	13.64
Utilized land	60.82	0.02	56.07	0.02	217.65	0.06	202.25	0.06	239.27	0.07

3.2. Data Sources and Processing

Data sources include (1) land-use remote sensing monitoring data. 2000, 2005, 2015, and 2018 remote sensing monitoring data of the Yangtze River Delta were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn (accessed on 1 January 2020)), which is based on Landsat TM/ETM+/OLI remote sensing image processing. The current land-use map was obtained after image pre-processing, manual visual interpretation, and other operations. The land-use types were divided into six categories, namely arable land, forest land, grassland, water, construction land, and unused land [45], according to the Classification of Current Land Use (GB/T21010-2017). The overall accuracy of the study area reached more than 80%, and the Kappa coefficient was above 0.70. (2) Statistical data. The socioeconomic data used in this study were obtained from the Shanghai Statistical Yearbook (2001–2019), the Jiangsu Statistical Yearbook (2001–2019), the Zhejiang Statistical Yearbook (2001–2019), the Anhui Statistical Yearbook (2001–2019), the China County Statistical Yearbook (2001–2019), and the China City Statistical Yearbook (2001–2019). (3) Nighttime light database. The data used in this study contain DMSP/OLS (version 4) from 1992 to 2013 and NPP/VIIRS (day/night band) from 2013 to 2018, which were obtained from the National Oceanic and Atmospheric Administration (https:// www.ngdc.noaa.gov/ngdc.html (accessed on 1 January 2020)). The data were processed using the maximum threshold method to remove background noise and temporary light interference with radiation correction. Subsequently, we referred to Li's method [46] for correction and fusion processing of the two types of data in order to ensure the accuracy and consistency of the study data. (4) Administrative boundary data. The administrative boundary data of the Yangtze River Delta were obtained from the National Basic Geographic Information Center of China (http://ngcc.sbsm.gov.cn (accessed on 1 January 2020)). Given the administrative boundaries adjustment and the above data's continuity, the study was subsumed and processed according to the latest administrative boundaries. In addition, since there is a gradual transition zone between built-up areas and suburban areas within municipal jurisdictions, splitting the two was not conducive to the totality of the study units, so the study combined and processed the municipal jurisdictions of each city in a unified manner. After reorganizing counties, county-level cities and municipal districts, 193 county units were identified (Figure 2).

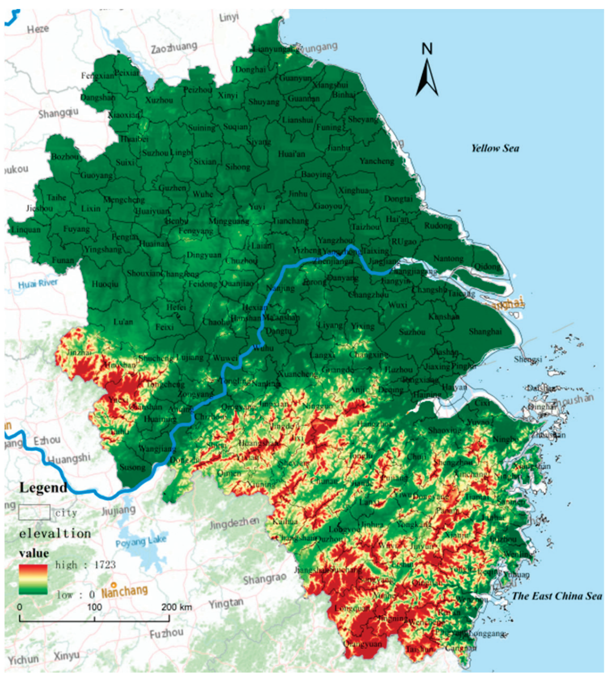

Figure 3. Study area.

3.3. Methods

3.3.1. Urbanization Evaluation Index System

The urbanization system is a multi-level and multi-factor complex system [1,17]. Scholars construct composite index methods from multiple levels such as population, ecology, society, economy, and land [47,48]. There may be multiple covariates, leading to bias in the evaluation results.

Since the 1960s and 1970s, Western society has entered a period of transformation and development. The United Nations, the World Bank, the Organization for Economic Cooperation and Development, and the European Union have paid unprecedented attention to environmental issues. Therefore, they have successively introduced indicator systems for evaluating sustainable development. To date, the mainstream indicator frameworks include Pressure-State-Response (PSR), Driving-Force-State-Response (DSR), Driving-Force-Pressure-State-Impact-Response (DPSIR), Vitality-Organization-Resilience frameworks (VOF), the human well-being/ecological health framework, and the thematic framework based on a factor–structure system. Among these, the thematic framework of the element–structure system can be decomposed by indicators, analyze the effect of each element on the target layer, and then select critical indicators. Based on the human–land relationship theory and the synergistic effect theory, this study comprehensively considers the advantages and disadvantages of individual indicators and comprehensive evaluation, draws on the research methods of most scholars [49,50], and identifies population urbanization, economic urbanization, and land urbanization as the key indicators of urbanization. The study identifies population, economic, and land urbanization as the primary indicators of urbanization evaluation [20,51]. It constructs the secondary indicators of population density, economy density, and spatial intensity based on scientific, comprehensiveness, and representativeness principles.

Population density and economic density: It is customary to use population data to be counted and aggregated at each level according to administrative units [52], which is large in scale, insufficient in dynamics, and unfavorable for overlaying with other geospatial data [53]. The downscaling method is mostly used in meteorological forecasting and spatialization of demographic and economic data [54,55], based on certain regression relationships. The original attribute information is converted into grid cells by weighting and summing the regression coefficients of different influence factors [56]. Land use is closely related to human activities and can be superimposed with other geographic factors in order to achieve integrated multivariate analysis; accordingly, this study chose a land-use model to spatialize population and economic data [57]. The height of the industrial structure is a symbol of prosperity and the flourishing of urbanization, and it is also a support for the continuous improvement of the regional economy [58,59]. This study selects urban land, rural settlements, and construction land, focusing on spatializing the economic density of secondary and tertiary industries. Please refer to the literature for the specific spatial regression method [60].

Spatial intensity (total light intensity): In the spatial dimension of urbanization, most studies follow the statistical yearbooks of built-up areas or extract remote sensing image information, but they can only analyze the quantitative expansion process of different sections of urban land, while the spatial expansion of urban land includes information on spatial structure and morphological structure, while mining the spatial combination and evolution of urban land is more conducive to the intensive utilization of resources and model exploration [61]. DMSP/OLS data can effectively monitor the urban land expansion process [62], often analyzing urban spatial processes, utilizing total light intensity [63]. The calculation method is as follows.

$$SN_a = \sum_{i=\min(DN)}^{\max(DN)} (DN_{\mathrm{i}} \times n_i) \tag{1}$$

In the formula, SN_a stands for the total light intensity of an area; DN_i stands for the grayscale value of i unit; n_i stands for the total number of pixels of i unit. SN_a reflects the intensity of human activities and indirectly reflects the intensity of urbanization and the spatial extent. This study uses this as a characterization of land urbanization.

3.3.2. Ecological Risk Assessment

Risk plot determination: Landscape structure and landscape dynamics have significant scale effects, and different scales have a greater impact on the results of landscape pattern analysis. By choosing an appropriate scale domain analysis, we can effectively reveal the research phenomenon's patterns and processes or things [64]. The landscape risk plot was empirically selected as 2–5 times the average area of the landscape patches in the study area for multiple debugging [65]. Therefore, we chose a 5 km × 5 km grid with equal spacing systematic sampling method. At last, a total of 181,705 sample plots were generated, which can reflect the spatial differentiation pattern. According to the ecological risk index model, the ecological risk index of each sample point is calculated and assigned to the center point of each sample point. Then the spatial pattern characteristics of ecological risk in the study area are analyzed by a Kriging spatial interpolation method.

Landscape index calculation: The component composition of the landscape and its spatial form can be reflected using the landscape pattern index [64]. Landscape risk mainly depends on external factors (anthropogenic disturbance) and internal factors (the ability of the landscape to maintain its own ecological stability) [23]. However, there is no best method to measure the landscape risk index, which is mainly based on the study scale and land use of the study area. Therefore, with reference to previous studies [35–37], we measured the landscape dominance index (D), the fragmentation index (C), and the separation index (F), and constructed the landscape disturbance index. Then we combined an expert scoring method, a hierarchical analysis method and a literature analysis method to construct the landscape vulnerability index. Finally, we established the loss index. Fragstasts 4.2 and Patch Analyst were used to calculate each landscape pattern index; the expressions and ecological meanings of each landscape index are referred to in the manual of Fragstasts 4.2.

Ecological risk evaluation: Land use landscape components are more accessible to preserve and obtain than ecological monitoring information. Using the area weight of each land-use type allows us to construct a land-use ecological risk index which can better reflect the ecological risk level in the sample area. The spatial sampling method was used to obtain the spatial representation of ecological risk, reflecting the ecological processes of regional landscape patterns or the influence of functions [66]. The calculation formula was as follows.

$$ERI_k = \sum_{i=1}^{m} \frac{A_{k\mathrm{i}}}{A_k} \times L_i \tag{2}$$

ERI_k is the ecological risk index of the k sample area of the landscape. L_i is the landscape loss index. A_{ki} stands for the study area, A_k is the area of the k sample area, m is the number of land-use types in the sample area grid, and i stands for the six different land-use types.

3.3.3. Coupling Coordination Degree Model

(1) Coupling degree function

Using the concept of capacity coupling in physics and the model of a capacity coupling coefficient, the coupling degree model of multi-system (or element) interaction is generalized. Therefore, the change coupling degree function between population urbanization, economic urbanization, and land urbanization can be expressed as [67].

$$C = \left((u_1 \cdot u_2 \cdot u_3)/((u_1 + u_2 + u_3)/3)^3\right)^{\frac{1}{3}} \tag{3}$$

In the formula, C stands for the coupling degree of population urbanization, economic urbanization, and land urbanization, and $C \in [0, 1]$, u_1, u_2, u_3 are the combined index values of population urbanization, economic urbanization, and land urbanization, respectively.

(2) Coupling coordination degree model

The coupling coordination model reflects the coordination status in the changing interactive coupling process of population urbanization, economic urbanization, and land urbanization, which is calculated as:

$$D = (C \times T)^{1/2} \tag{4}$$

$$T = a \times u_1 + b \times u_2 + c \times u_3 \tag{5}$$

In the formula, D stands for the coupling coordination degree, C stands for the coupling degree; T stands for the combined index values of population urbanization, economic urbanization, and land urbanization; u_1, u_2, and u_3 stand for the combined development of the level of population urbanization, economic urbanization, and land urbanization, respectively; a, b, and c are the coefficients to be determined, and considering the regional characteristics, this study adopts the equal weight method to set the value of all three coefficients to 1/3, aiming to improve the overall urbanization level.

3.3.4. Change Trend Analysis

The changing trend between two variables can be analyzed using the slope in a one-dimensional linear regression equation. This study selected an urbanization coupling coordination degree and ecological risk as independent variables, and times as the dependent variable, respectively. The slope of the one-dimensional regression equation is used to analyze the trend of changes in the independent variables using the least-squares method [62]. The calculation formula is as follows:

$$k = \frac{n \times \sum_{i=1}^{n} (i \times S_i) - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} S_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \tag{6}$$

In the formula, k stands for slope, n stands for the number of time points; i stands for time; and S_i is the statistical number of image elements.

4. Results

4.1. Spatio-Temporal Development Process of Urbanization's Coupling Coordination Degree in the Yangtze River Delta

From 2000 to 2018, the urbanization coordination level in the Yangtze River Delta continued to improve, and the speed continued to accelerate. The coupling coordination degree increased from 0.0116 to 0.0687, with a change rate of 494.27%. This indicates that urbanization development in the Delta is in a high-quality development stage of integrated, multidimensional, comprehensive, and coordinated urbanization. Based on the natural fracture method, the urbanization coupling coordination degree was divided into five levels from low to high: unsatisfactory coupling coordination degree (<0.0980); low coupling coordination degree (0.0980–0.3057); medium coupling coordination degree (0.3058–0.4782); high coupling coordination degree (0.4783–0.6545); and satisfactory coupling coordination degree (>0.6546) (Figure 4).

In 2000, the coupling coordination of urbanization in the Yangtze River Delta was weak (0.0116). The unsatisfactory coupling coordination patches accounted for 96.45%, which were widely distributed in a continuous pattern throughout the region. There were 8427 (2.41%) patches with a low coupling coordination, which were wrapped around the periphery of the satisfactory coupling coordination patches in a circular pattern, clustered in the periphery of the central cities and irregular in shape; 1430 (0.41%) patches of medium coupling coordination were distributed in a scattered pattern in the central towns, and 1551 (0.44%) high coupling coordination map units were adjacent to the satisfactory coupling coordination map units. The number of satisfactory coupling coordination map units was only 0.29%, mainly concentrated in the central cities (Shanghai, Nanjing, Hangzhou, Suzhou-Wuxi-Changzhou, etc.)

In 2005, the coupling level of urbanization in the Yangtze River Delta was enhanced compared with that in 2000, and the mean value of regional coupling coordination was

0.0226, which was still low. Regional differences tended to soar and the satisfactory coupling coordination degree was concentrated in the central cities, and the east–west divergence was strengthened. Among them, the number of unsatisfactory and low coupling coordination spots was 6457 less than that in 2000, but the proportion was still as high as 97.01%; the number of medium coupling coordination spots was 3423 more, which presented a belt-type spreading trend in the line of Shanghai, Suzhou-Wuxi-Changzhou, and Nanjing. Hangzhou, Ningbo, and Hefei showed signs of patchy intensification more strongly. The number of higher coupling coordination map units increased (2933 in total) and were mainly located between higher and lower coupling coordination map units, with buffering and transition effects. The number of high coupling coordination map units increased significantly (1652 map units in total) spatially, with Shanghai, Nanjing, Suzhou-Wuxi-Changzhou, and Hangzhou as the multipolar centers.

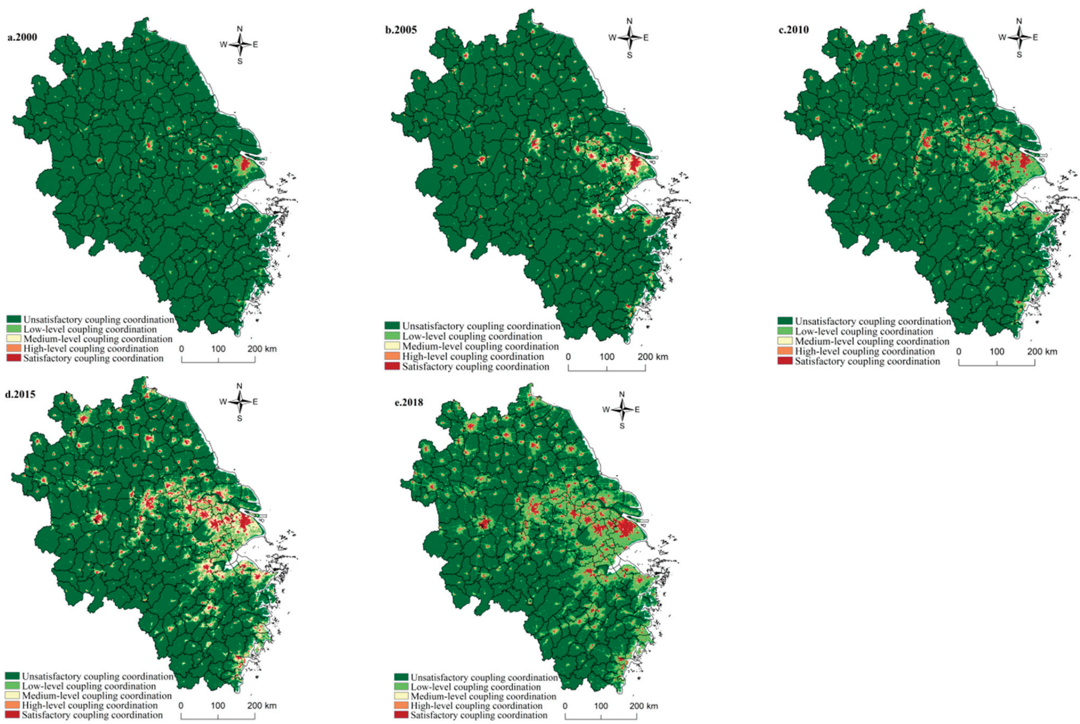

Figure 4. Spatial pattern of urbanisation coupling coordination degree in the Yangtze River Delta from 2000 to 2018.

In 2010, the degree of urbanization coupling and coordination in the Yangtze River Delta continued to increase with an average value of 0.0415. The county gap widened, and the east–west differentiation characteristics were further locked. The proportion of unsatisfactory coupling and coordination map units decreased to 87.15%, but spatial distribution did not shift much compared with the past. The number of low coupling coordination degree map units increased, with the proportion rising to 7.16%, showing a Z-type spatial pattern mainly concentrated in the surrounding areas, such as Shanghai, Hangzhou-Jiaxing-Huzhou, and Suzhou-Wuxi-Changzhou. The number of medium coupling coordination map units also decreased, which were scattered in the center of each county unit in the form of sporadic points; higher coupling coordination map units accounted for 1.43%, spreading from the central city to the surroundings in a radiation diffusion way; the satisfactory coupling and coordination map units had an axis development trend compared to before, with the clusters in the Hefei, Ningbo, and Xuzhou city centers beginning to increase.

In 2015, the coupling coordination of urbanization in the Yangtze River Delta rose slightly, with the mean value of regional coupling coordination increasing slightly to 0.0578. At the same time, the regional differences narrowed, and the polarization center jumped the overall spread. The number of unsatisfactory coupling coordination map units in Shanghai, southern Jiangsu, and northeastern Zhejiang transitioned to a lower coupling coordination; the number of unsatisfactory coupling coordination map units in the region decreased, and the proportion of lower coupling coordination map units increased significantly (12.81%). The number of medium coupling coordination map units and the spatial distribution range increased, with the structural characteristics of spatial balance beginning to emerge. The change in the number of units and the spatial spread of the higher coupling coordination map units were not significant. The number of units of satisfactory coupling coordination map spots further increased to 7746, the network-like structure of the southern Jiangsu region appeared, and the central map units of Hefei City and Xuzhou City continued to expand.

In 2018, the degree of urbanization coupling coordination in the Yangtze River Delta continued to increase, with the regional average value of coupling coordination being 0.0687. However, the regional difference transitioned from polarization to equilibrium. The proportion of unsatisfactory coupling coordination degree map units dropped to 71.33%. The proportion of low coupling coordination degree map units quickly increased to 23.86%, Shanghai-Sunan-North Zhejiang became a continuous patch and a subtle line between the high and low values in northern Jiangsu and northern Anhui regions was revealed, which was related to the implementation of the Yangtze River Delta integration policy, truly regional connections and strengthened integration. The medium and high coupling coordination degrees changed slightly compared with 2015. The number of map units in the satisfactory coupling coordination degree was still increasing (7868), in which the spatial distribution had the characteristics of 'one pole, many strong small centres'. Shanghai was the core, and Suzhou-Wuxi-Changzhou, Nanjing, Hefei, and other provinces were the strengthening zones, with jumping spreading forms of sporadic minor strengthening points in northern Jiangsu, northeastern Zhejiang, and northern Anhui.

The coupling coordination degree of the Yangtze River Delta's urbanization has two characteristics. (1) From the perspective of pattern characteristics, the spatial distribution of urbanization coupling coordination degree has path-locking characteristics. Satisfactory coupling coordination decreased from the core to the periphery, mainly in Shanghai, Suzhou-Wuxi-Changzhou, Nanjing, and Hangzhou. However, the higher and medium coupling coordination degrees did not fully play the roles of transition and link, respectively. (2) In terms of evolution characteristics, from 2000 to 2018, the evolutionary context of urbanization coupling coordination degree in the Yangtze River Delta had an overall trend of localized agglomeration points to whole spread. 2000–2010 was the polarization stage of urbanization coupling and coordination degree to the agglomeration of regional central cities, in which regional, inter-provincial, and intra-county differences increased due to the gradient of economic development, the hierarchy of the industrial structure, the trend of population movement and the efficiency of resource utilization. In addition, the polarization process gradually transformed from the initial single-core agglomeration center (Shanghai) to the multi-core agglomeration point (Nanjing, Suzhou-Wuxi-Changzhou, Hangzhou) at the same time as the scope of polarization spread grew. Afterwards, as the integration of the Delta became a national development strategy in 2007, it entered the diffusion stage of urbanization coupling coordination degree after 2010, and the state of balanced regional development began to appear. In northern Anhui, northern Jiangsu and northeastern Zhejiang, there were many map units of satisfactory coupling and coordination degree. The diffusion model was also transformed from radiation diffusion and hierarchical diffusion to jump-diffusion.

4.2. Spatiotemporal Evolution Characteristics of Ecological Risk in the Yangtze River Delta

The regional risk value was divided into five levels based on the natural fracture method: low risk (0–0.0061), lower risk (0.0062–0.0092), medium risk (0.0093–0.0121), and higher risk (0.0121–0.0203) and high risk (>0.0203). After spatial interpolation, the spatial distribution map of ecological risks in the Yangtze River Delta from 2000 to 2018 (Figure 5) was derived. With the help of regional statistical tools, the risk values in different regions and periods were obtained.

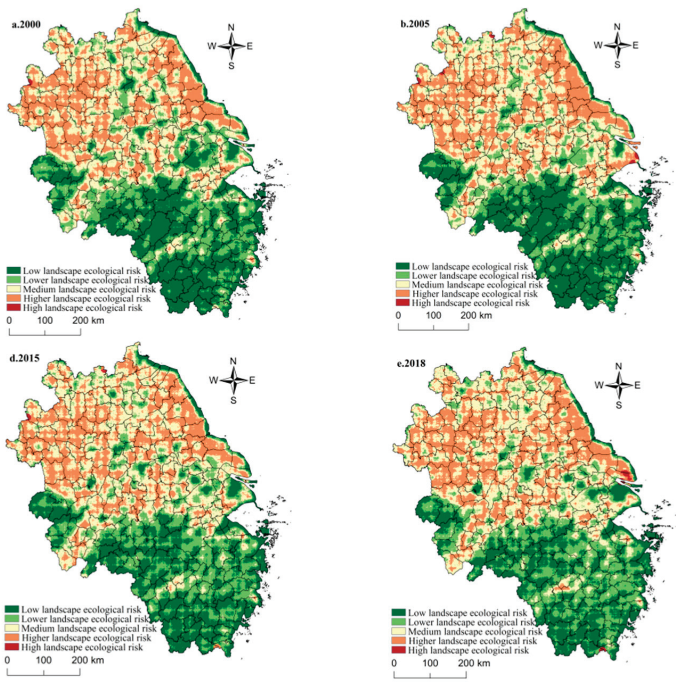

Figure 5. The spatial pattern of ecological risk in the Yangtze River Delta from 2000 to 2018.

From 2000 to 2018, ecological risk in the Yangtze River Delta tended to weaken, dropping from 0.0091 to 0.0082, with a change rate of −10.03%. Spatially, the distribution of risk values was characterized by a pattern of homogeneous aggregation and heterogeneous isolation, with a high north and a low south and a manifest circle structure. Specifically, in 2000, the average ecological risk of the entire region was 0.0091. The low and lower ecological risk areas occupied the dominant position (accounting for 26.42% and 21.88%, respectively) and were mainly distributed along the northern part of the southern Anhui Mountains to the Taihu Lake Rim, such as the Dabie mountains, the Taihu Lake Plain and mountainous and hilly areas in southwestern Zhejiang (e.g., Shucheng, Suzhou, Longquan, Qingyuan, Chun'an, etc.) Water and woodland were the dominant landscapes in these areas, so the overall landscape dominance and connectivity were high(Figure 6). The proportion of medium and higher risk areas was relatively large (50.17%), forming a heterogeneous pattern of north–south isolation from low-risk areas, especially in the northeastern coast of Jiangsu and the northern plains of Anhui, where the risk was relatively high (e.g., Sheyang, Dongtai, Suixi, Huaiyuan, etc.) Arable land and construction land were embedded in the medium- and high-risk areas, causing patches in these areas to be cut easily by transportation land and water. Hence, the land structure was diverse and complex, resulting in high separation and loss. High-risk areas accounted for a small proportion (0.05%). They were mainly distributed across areas with an apparent expansion of built-up areas (e.g., Bozhou, Suzhou, etc.) because construction land invades cultivated land and ecological land, resulting in increased regional fragmentation.

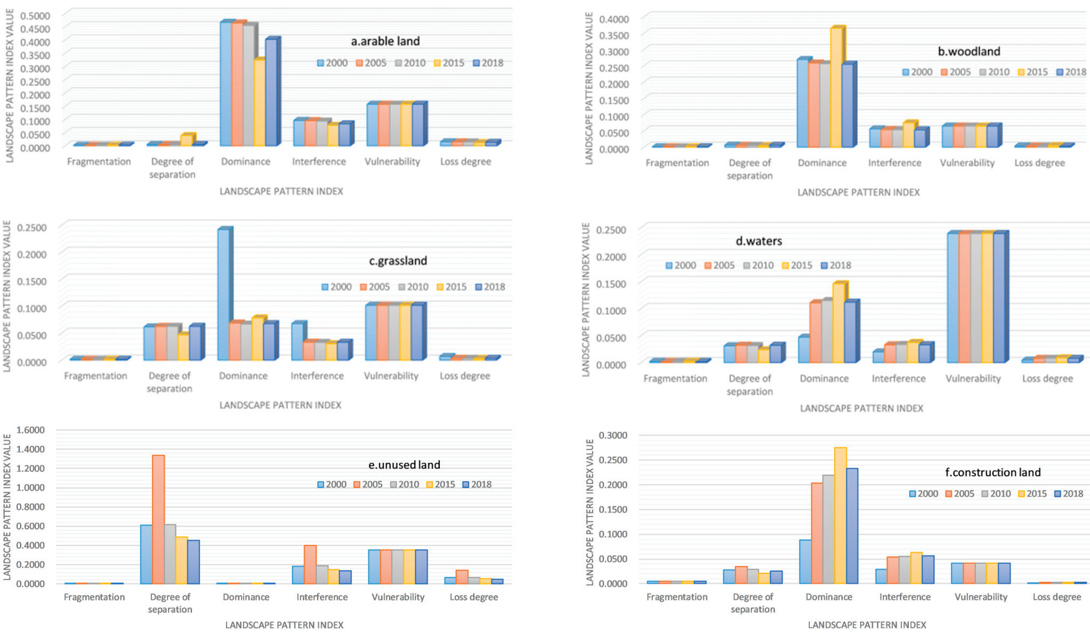

Figure 6. The landscape pattern index of the Yangtze River Delta from 2000 to 2018.

In 2005, the ecological risk value of the Yangtze River Delta slightly increased (0.0095), but the areas of low and lower ecological risk decreased to 45.46% compared to 2000. During this period, construction land occupied more arable land, which decreased by 3788.84 km^2. Hence, the predominance and interference degree of construction land was significantly increased, indicating that the interference effect of human activities had increased. The areas of medium risk and higher ecological risk increased to 54.35%. Due to the expansion of construction land, it was still mainly external expansion that was squeezing ecological land use and arable land, exacerbating extensive and acceptable land use in built-up areas and in urban–rural transition zones. The separation of construction land and unused land increased significantly, which exacerbated regional ecological risks. High ecological risk areas were concentrated in Shanghai, Bozhou City and other places (0.19%); these areas were mainly composed of water and cultivated land with greater vulnerability, high intensity of human activities, significant landscape heterogeneity, and high risks.

In 2010, the regional risk decreased (0.0091), the proportion of medium risk areas was still high (28.19%), and the spatial impact spread to northern and southern Jiangsu and the Hangzhou-Jiaxing-Huzhou regions. For all the regions referred to, construction land and unused areas with high fragility were expanded such that loss and interference increased immediately (Figure 5). The areas of low risk and more low risk increased by 1.70% compared with 2005, as the picture of ecological risk in Zhejiang and the southern Anhui mountainous areas with high vegetation coverage gradually decreased. Lastly, higher and high ecological risk areas did not change much (the proportion increased by only 0.16%).

In 2015, the expansion of built-up areas in the Yangtze River Delta was restricted by policies. Therefore, ecological risks were reduced, with a regional average of 0.0083. The higher ecological risk area gradually degenerated into a medium risk area, leading to the medium risk area increasing to 30.75%. The fragmentation of the regional landscape also decreased; in particular, the fragmentation of construction land decreased significantly

(−0.0024). At the same time, the measures of retreating from farming and lakes and protecting forest land were vigorously implemented, thereby enhancing the advantageous degree of green ecological lands such as forest land and water. The low risk and lower risk areas remained at 46.58%. Meanwhile, in the northwest and central Zhejiang, the large low ecological risk areas tended to shift to lower risk areas, resulting in a decrease of 3.97% of the total low-risk areas, which is related to the encroachment of forest land due to the significant expansion of arable land and construction land in the district during this period.

In 2018, the ecological risk of the Yangtze River Delta was still showing a slight decline. However, in southern Anhui, Zhejiang mountainous and hilly areas, the low-risk range was narrowing, causing the overall low ecological risk areas to climb to lower ecological risk areas and medium risk areas. As shown in Figure 4, the three areas accounted for 20.89%, 24.56%, and 24.03%, respectively. The areas with high ecological risks did not change much.

In conclusion, the ecological risks of the Yangtze River Delta were deeply affected by rapid urbanization, in which the fragility (internal factors) and disturbance (external factors) of landscape components together formed a spatial differentiation pattern of regional ecological risks. On the one hand, high and higher ecological risk areas were concentrated around built-up areas and urban–rural transition zones, while low and lower ecological risk areas were concentrated around waters and woodlands; on the other hand, the isolation of high–low ecological risk areas was evident.

4.3. Ecological Risk Response Pattern of the Coupling Coordination Development of Urbanization in the Yangtze River Delta

Previous studies on urbanization and the ecological environment mostly drew conclusions based on their quantitative correlation analyses, such as the standard heterogeneous growth model, coupling coordination, elasticity coefficient, decoupling analysis, Pearson correlation, grey correlation, and STIRPAT analysis. There are many ways to associate things, such as direct/indirect and internal/external, but correlation analysis provides only one phenomenon. A positive correlation between the two does not mean promotion and enrichment, whereas a negative correlation does not necessarily mean they inhibit each other. Thus, there should be some similarities in their development process and ways, and urbanization's ecological risk response mechanism is far more complex than its appearance [40]. Hacken's synergy considers the synergy between complex systems, such as the coordination and cooperation between components under the control of sequential parameters, to promote the development of the overall system in the same direction in order to finally achieve the order of the overall system [68]. Accordingly, the current study used the least-squares method to fit the 1-D linear regression equation and employed geographic information mapping to achieve the interrelated analysis of the trend changes between the two.

From 2000 to 2018, the coupling coordination degree of urbanization in the Yangtze River Delta increased, while the ecological risk of the landscape tended to decrease (Figure 7), indicating that the coercion of urbanization on the ecological environment was improving, consistent with the findings of existing empirical studies [69]. The rapidly increasing urbanization coupling coordination zone area accounted for about 20.04%. It was distributed in a polycentric set-core pattern in Shanghai, Suzhou-Wuxi-Changzhou, Hangzhou-Jiaxing-Huzhou, Nanjing-Zhenjiang-Yangzhou, and Hefei metropolitan areas with a high degree of integration, where geographical location, population distribution, industrial structure and traffic arteries significantly influenced the degree of synergy. Meanwhile, development was slightly lagging in northern Jiangsu, northern Anhui, and the central Zhejiang basins and hilly areas, scattered in a point-axis or stripe pattern. This finding indicated that the stage of economic, social development and topography were also factors affecting the degree of urbanization coupling coordination [42]. The rising and slowly rising areas mainly surrounded the edge of the built-up areas. Nevertheless, the degree of urbanization coupling coordination on a large scale decreased, mainly in the mountainous hills around the Yangtze River and lakes and the Yellow and Huaihai plains; this decrease was related to differences in technology level, industrial structure, environmental protection, the threat of water pollution and water disasters (e.g., eutrophication of rivers and lakes, groundwater pollution, etc.) and soil pollution (e.g., soil slabbing, heavy metal pollution, etc.), such as that triggered by domestic sewage, industrial wastewater, and agricultural surface source pollution. All these are still serious, indicating that the overall coordinated urbanization development in the Yangtze River Delta region is still at the developmental stage and requires vigilance against the infiltration and the transfer of low-end industries in areas with advantageous coordinated urbanization development.

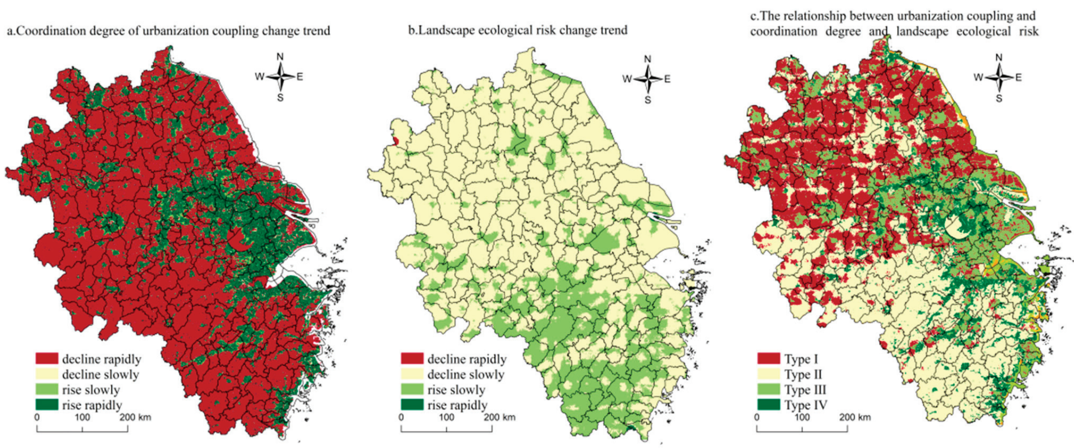

Figure 7. Changes of the Coordination Degree of Urbanisation and Ecological Risks in the Yangtze River Delta from 2000 to 2018.

Figure 7b depicts the apparent trend of regional ecological risk decreasing in the north and increasing in the south. The landscape ecological risk tends to increase in the Dabie mountains, the mountains of southern Anhui, the hilly areas of western Zhejiang, the mountains of southern Zhejiang, the ring of Taihu Lake, Hongze Lake, the northern coast of Jiangsu and the estuary of the Yangtze River, indicating that the urbanization process has a more robust response to the stress of the ecological environment. Ecological risk gradually decreased after spreading outward from the above ecological land because the ecosystem was resilient and self-healing and more vulnerable to solid disturbance by human activities. Above all, it is necessary to strengthen territorial spatial planning by setting the necessary bottom line and resilient space according to the resource and environmental carrying capacity and by coordinating the ecological safety space and social development.

The inverse correlation between urbanization coupling degree and ecological risk in the Yangtze River Delta was the central dynamic of regional development (Figure 7c). Guided by policies such as ecological reforestation, urban greening, green eco-efficiency and the return of farmland and lakes (forestry), the increased coordination of urbanization coupling in Zhejiang Province, Jiangsu Province and Shanghai effectively reduced local ecological risks. More than that, the industrial structure, science and technology, and population quality in these regions were better, and pollution control and environmental awareness were higher. Nevertheless, many Type I pixels appeared in the majority of Anhui Province and northern Jiangsu Province, indicating that the ecological risk of urbanization in the late-developing areas may be more challenging to manage. This was since, on the surface, these areas undertake industrial transfer, which temporarily and rapidly improves the local urbanization process, but the risk leads to concealment and lag and long-term accumulation of risk explosive progress in the process. The number of Type IV pixels was tiny (3.85%), mainly located in the area around Taihu Lake, where the intensity of human social activities was high. However, with the awakening of ecological awareness and the improvement of ecological compensation mechanisms in the Taihu Lake basin, this type will gradually shrink.

Type I indicates that the coupling coordination degree of urbanization and the ecological risk of landscape decrease. Type II indicates that the coupling coordination degree of urbanization increases and the ecological risk of landscape decreases. Type III indicates that the coupling coordination degree of urbanization decreases and the ecological risk of landscape increases. Type IV indicates that the coupling coordination degree of urbanization and the ecological risk of landscape increase.

To comprehensively and deeply explore multidimensional urbanization and its ecological risk response, the urbanization system was decomposed into crucial dimensions, such as population, economic, and land [18]. The results show the following:

Population urbanization: During 18 years, the total population of the Yangtze River Delta increased rapidly, with an average annual increase of 1,487,900 people/year (14.34%). The regional average population density also increased from 101 people/km^2 to 249 people/km^2, reaching 146.53%. These figures indicated that the population attractiveness of the Yangtze River Delta was solid and sustainable. Spatially, the inflowing population in the Delta continued to cluster in the central cities and had a moderate tendency to disperse, with Shanghai as the polarization center; population densities in Suzhou-Wuxi-Changzhou, Hangzhou-Shaoxing-Ningbo, and Nanjing-Zhenjiang-Yangzhou were also growing faster (Figure 8). Population density and consumption level in the Yangtze River Delta were growing simultaneously, and according to the statistical yearbook of the provinces and cities in the Yangtze River Delta, the average annual consumption expenditure per person in urban households in the Delta from 2000 to 2018 increased by an average of RMB 6230.84 per year, posting a growth rate of 394.23%. Consumption was the endogenous driving force of urban economic development. Dense population and growing consumption levels form an endogenous circulatory system while people consume limited regional resources (e.g., land, water, infrastructure, public services, etc.) The proliferation of household consumables and pollutant emissions had likewise placed tremendous pressure on the bearing capacity of resources and the environment, resulting in an increased probability of ecological risk threats.

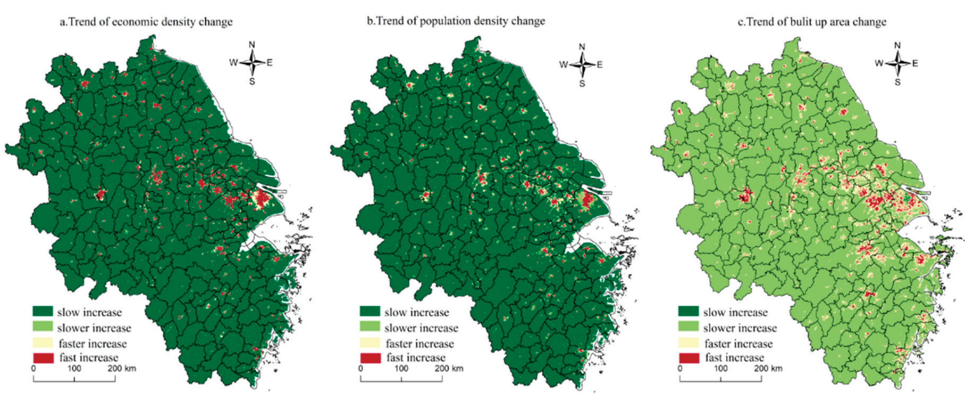

Figure 8. Changes of economic urbanization, population urbanization, and spatial urbanization in the Yangtze River Delta from 2000 to 2018.

Additionally, according to the China Education Expenditure Statistical Yearbook (2001–2019), due to the additional $7,246,059.20 investment in education expenditure in the Yangtze River Delta from 2000 to 2018, education in the Delta region has developed steadily. The population quality had improved significantly, making the region one of the most highly educated regions Chinese. On the one hand, high-quality population groups contributed to the formation of green culture and environmental awareness, low-carbon consumption and green travel habits; on the other hand, they also promoted technological progress, clean production and energy use efficiency. Eventually, the moderate population size and high population quality will mitigate ecological risks.

Economic urbanization: Economic density increased from 586,700 yuan/km^2 in 2000 to 25,919,600 yuan/km^2 in 2018. The rapid increase in industrialization induced frequent air pollution, water pollution and soil heavy metal pollution. According to scholars, the overall PM2.5 concentration in the Yangtze River Delta from 2000 to 2017 was upward, and the air quality was worrying [70]. Notably, the haze was not a local environmental dilemma. However, it would produce spatial spillover effects due to the diffusion or transfer of atmospheric circulation and other factors, easily expanding the spatial extent of ecological risk threats. The problems of domestic sewage and agricultural and industrial wastewater in the Yangtze River Delta were also prominent, leading to repeated environmental stress problems such as cyanobacteria in Taihu Lake and black water in Hongze Lake. The Yangtze River basin was located in the lower reaches of the Yangtze River, where many noxious substances from the upper and middle reaches gather downstream and where sediment precipitation and runoff velocity decrease, making it difficult to self-clean the accumulated harmful substances. The majority of heavy industrial plants (e.g., petrochemical plants, iron, and steel plants, etc.) in the Yangtze River Delta were also built along the river, so solid industrial discharges were dispersed with the water flow, spreading the ecological risk in a point-to-point and comprehensive manner. However, the development of industrial coercion of the ecological environment was not continuously serious; with the awakening of ecological awareness, capital accumulation and technological progress, such a development could also promote the upgrading and adjustment of the industrial structure, the process of energy-saving and emission reduction technology, and the emergence of the lightweight and clean industry. Furthermore, it could reduce non-desired output, improve green ecological efficiency, and further spread clean production technology. At the same time, the five major central cities of Shanghai-Nanjing-Suzhou-Hangzhou-Ningbo have taken on the phenomenon of industrial transfer, and the 'retreat of two into three' has led to the mitigation of local ecological risks.

Land urbanization: Land urbanization was manifested by the increase of non-agricultural land and the decline of agricultural land, which would very likely change the soil sub-bedding surface, increase the impervious surface, and affect the surface runoff and local climate circulation among various other outcomes, thus changing soil properties through natural factors such as rainfall-intensified soil erosion and enriched soil heavy metal pollution elements. From 2000 to 2018, the average nighttime light intensity in the Yangtze River Delta increased from 0.23 to 2.26, with the area of urban construction land also increasing from 5754.84 km^2 to 17,179.55 km^2. These figures indicated that the built-up area expanded rapidly during the study period, mainly in an outward expansion and encroaching on the natural ecological land in the surrounding areas. According to the study, urban land expansion in the Yangtze River Delta was mainly driven by population and economic development [71]. However, more population inflows would increase the spatial demand for urban infrastructure construction.

Furthermore, the increasing price of land in the central city led to rising production costs for enterprises, forcing commercial, industrial, and residential land use to the far suburbs. At the same time, the disorderly expansion and lack of functional land-use planning resulted in a disorderly and inefficient land-use structure or overly mixed, high-intensity structures in some areas, with a large amount of idle land, abandoned land, and urban villages. In addition, due to outward expansion and uneven development, the development zone fever and real estate fever at the expense of arable land resources were also important factors, with the total real estate development investment in the Yangtze River Delta growing at a rate of 152.646 billion yuan/year from 2000 to 2018. However, after strict restrictions on the expansion of built-up areas, delineation of urban growth boundaries and implementation of territorial spatial planning, the outward spreading of urban land has ceased, and the ecological risk pressure, reduced.

In summary, the spatial and temporal differentiation of ecological risks of urbanization arises from the differences in population aggregation, economic and social development levels, and expansion trends of built-up areas. Ecological risks are not local environmental problems, but are dynamic, holistic, open, lagging, hidden, and uncertain. The mutual synergy of population urbanization, economic urbanization, and land urbanization is necessary to achieve the linkage cooperation of factor concentration/diffusion, population quality promotion, technological progress, and industrial structure upgrading to realize the control and prevention of the ecological risks of urbanization (Figure 9).

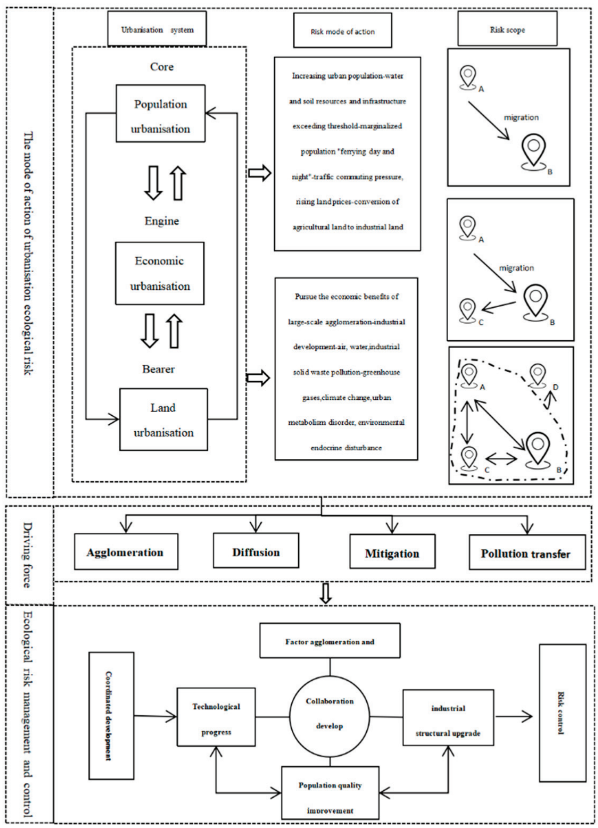

Figure 9. Driving Mechanism of Urbanization Ecological Risk.

5. Conclusions and Discussion

5.1. Discussion

5.1.1. Research Applicability

The relationship between urbanization and the ecological environment is a research hotspot in this field [15,72,73]. Due to the different characteristics of urbanization in different regions, the ecological risks caused are also different [18,70]. The different development stages also create ecological risks of different degrees, scopes, and modes. The Yangtze River Delta is an important region for China to implement high-quality development strategies, and the relationship between urbanization development and ecological protection is complex. On the one hand, urbanization development accumulated capital and talents and promotes industrial structure upgrading and production technology innovation; on the other hand, urbanization threatens the natural environment, causing pollution, destruction and collapse of the ecosystems. Therefore, it is significant to explore the characteristics, patterns and ecological risk distributions of urbanization in different regions of the Yangtze River Delta across different periods.

In addition, this study goes beyond the limitation of using administrative units as data carriers by integrating multiple data sources with multiple methods. Instead, we used a finer raster scale to measure the coupling coordination of multidimensional urbanization and its spatiotemporal variation of ecological risk in the Yangtze River Delta region from 2000 to 2018. This broadens the cognitive perspective and research scale of urbanization ecological risks.

The root cause of ecological risk lies in the development stage and development mode of urbanization [18]. Therefore, the urbanization and the industrialization process are not the same for "countries such as the United States, the United Kingdom, Japan, Korea, Brazil, India and Pakistan", nor for China. Urbanization and industrialization patterns in the wider region in which the study area is sited—that is east Asia and China—differ from those of older industrial countries in Europe and North America. The same stands for the role of industrialization, which is not anymore the driving force of urbanization in Europe and North America, as the tertiary sector is the most important in terms of economic development. The United States and Europe, for example, are more concerned with urban ecological patterns, ecosystem services, human habitat, and even public health risks, as well as persistent severe air pollution, increased ozone concentrations, the greenhouse effect, acid rain and increased concentrations of airborne particulate matter. With the rapid development of urbanization in China, the ecological and environmental problems caused by it also have attracted extensive attention from the government, society and scholars, and the research content has evolved from focusing on the impact of land use change on single elements of the ecological environment, such as climate, hydrology, soil, and biology, to the research on the impact of land use change on the overall ecological environment of the region.

The present study showed that in the past 18 years, urbanization coupling coordination in the Yangtze River Delta was negatively correlated with ecological risks. This showed that in the context of ecological civilization, regional integration and high-quality development, the ecological risks in this region had been highly valued. Therefore, the two-way virtuous circle and sustainable development of local urbanization and ecosystem optimization and the total value of ecological risks tend to decrease gradually. However, it should be noted that, at the regional level, on the whole, it is still necessary to strengthen the linkage regulation and overall optimization of ecological risks in different development stages and different development styles.

5.1.2. Shortcomings and Future Prospects

Due to the complexity of multidimensional urbanization and the uncertainty of risks, this study's urbanization and risk evaluation criteria were still inconsistent, and it is not easy to obtain primary research data. Owing to the complexity of multidimensional urbanization and the uncertainty of risks, the criteria of urbanization and risk evaluation in this study were still inconsistent, and it is not easy to obtain primary research data. Several shortcomings should be mentioned. ① First, the core indicators of urbanization lacked consideration of human elements for the spatialization of coordinated urbanization development. For instance, social structure changes lacked the necessary questionnaires, in-depth interviews and big data mining. ② Second, lack of policies, zoning adjustments and other changes on the nonlinear effects of ecological risk analysis. In the next step, we will make use of big data (i.e., cell phone signaling, microblog sign-in and mobile population data), questionnaire surveys and Participatory Geographic Information System (PPGIS) to select more specific stage sample points and to further explore the influence mechanisms of collaborative urbanization development on ecological risks from different spatial and temporal scales.

5.1.3. Policy Implications

According to the findings of the article, in order to mitigate the ecological risks of urbanization, the following policy recommendations are proposed: ① First, the construction of a regular ecological risk monitoring and early warning system should be strengthened. Environmental protection departments need to monitor the spatial and temporal extent of air pollution, water pollution, soil pollution, habitat destruction, and intensity of disturbance during the development of urbanization in real-time. Thus, a strict early warning system must be established to reflect and intervene promptly on the results of risk reporting. ② Second, the concept of green, efficient and harmonious development should be established. New industries need to be developed, such as product development, design, financial transactions, services, and logistics and e-commerce, by promoting the optimization and upgrading of the industrial structure of the Yangtze River Delta. Additionally, attention must be directed toward promoting the division of labor and collaboration between regions and the construction of industrial chains to avoid the 'siphon effect' arising from the 'pollution transfer' caused by one pole alone. ③ Third, we should establish the awareness of spatial planning of national land from top to bottom and from bottom to top. Given the rapid and disorderly expansion of construction land, we should adhere to the concept of spatial governance and urban–rural integration. Based on the evaluation of the carrying capacity and on the suitability of resources and environment, we should adhere strictly to the bottom line of 'green line', 'blue line', and 'red line'; plan and coordinate the regional 'agricultural space', 'urban space', and 'ecological space'; and strengthen the improvement of human living environment and ecological environment construction. ④ Last, the strategy of zoning control and necessary treatment should be implemented. Studies showed apparent regional differences between the degree of urbanization coupling coordination and ecological risks. Therefore, key zones of risk warning control should be established in the built-up areas, urban–rural transition zones and around ecological lands with higher risk probability, such as the hilly areas in western Zhejiang, the mountains in southern Zhejiang, the ring of Taihu Lake, Hongze Lake, the northern coast of Jiangsu, and the mouth of the Yangtze River. The infiltration of low-end industries in developed areas should be appropriately avoided, and industrial transfer parks must be established for spatial guidance and control. The integration of secondary and tertiary industries in places such as Suzhou-Wuxi-Changzhou, Nanjing, Ningbo, and Hangzhou should be developed vigorously.

5.2. Conclusions

This study diagnosed the spatial and temporal patterns and trends of ecological risk response to coordinated urbanization development in the Yangtze River Delta from 2000 to 2018. It explored the impact of multidimensional coordinated urbanization development on ecological risk from the perspective of spatial linkage. The main findings were as follows:

(1) The overall coupling coordination degree of urbanization in the Yangtze River Delta increased. The satisfactory coupling coordination degree mainly decreased from the core to the periphery with the path-locking effect in Suzhou-Wuxi-Changzhou and Hu-Ning-Hang. However, the higher coupling and medium coupling coordination degrees do not fully play the roles of 'transition' and 'linking', respectively. In terms of evolutionary characteristics, due to the gradient of economic development, the hierarchy of the industrial structure, trend of population flow and difference in the efficiency of resource utilization, 2000–2010 was the 'polarization stage' at which the coupling coordination degree of urbanization transformed from single-core agglomeration to multi-core agglomeration points. Afterwards, it entered the 'diffusion stage'. The state of balanced development of the region started to appear, with the diffusion mode transforming from the initial radiation diffusion and hierarchical diffusion to jump-diffusion.

(2) From 2000 to 2018, the ecological risk of land use in the Yangtze River Delta tended to weaken, and the fragility (endogenous) and disturbance (exogenous) of landscape components combined to form a spatial differentiation pattern of homogeneous aggregation

and heterogeneous isolation of regional ecological risk. High and higher ecological risk areas were concentrated around built-up areas. In urban–rural transition zones, low and lower ecological risk areas were clustered around green areas (e.g., water areas, woodlands, etc.) The segregation of high and low ecological risk areas was more prominent.

(3) The increase in the degree of urbanization coupling and coordination in the Yangtze River Delta during the study period tended to reduce the ecological risk. Increasing urbanization coupling coordination in Zhejiang Province, Jiangsu Province and Shanghai City effectively reduced the local ecological risk. However, the simultaneous increase of urbanization coupling coordination and ecological risk still existed in most of Anhui Province and northern Jiangsu Province. These findings indicated that the ecological risk of urbanization in late-developing areas may be more difficult to manage. The hidden and lagging nature of the risk needs to be identified and prevented. In addition, the Taihu Lake Rim region hinted at the adverse effects of urbanization on ecological risks, but with the awakening of ecological awareness and the improvement of ecological compensation mechanisms in the Basin, ecological risks in this region would decline.

(4) The differences in population aggregation, economic and social development levels, and built-up area expansion trends were essential factors for the spatial and temporal differentiation of urbanization ecological risks. The synergy of population urbanization, economic urbanization, and land urbanization could link factor concentration/diffusion, population quality promotion, technological progress, and industrial structure upgrading and thus realize urbanization ecological risk control and prevention.

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Study on the Evolution, Driving Factors, and Regional Comparison of Innovation Patterns in the Yangtze River Delta

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Abstract: The differences in innovation, and the resulting inefficient allocation of innovation resources, are key factors affecting the high-quality development of urban agglomerations. In the context of China's upgrading of the integrated development of the Yangtze River Delta (YRD) to a national strategy, the study of innovation patterns and driving factors in this highly developed urban agglomeration provide references and experiences for high-quality development and innovation improvements in other urban agglomerations. Using prefecture-level patent data from 2000 to 2018, this study analyses the evolution characteristics of the innovation patterns in the YRD, from the perspective of innovation level and innovation growth, based on the coefficient of variation, locational Gini coefficient, and the relative development rate index. Then, using the knowledge production function, this study quantitatively explores the driving factors for innovation from multiple perspectives. The main findings are as follows. The differences in urban innovation levels decrease with improvements in the innovation level of urban agglomerations. In terms of the evolution of the spatial pattern of innovation levels, the "core–periphery" and "south–north" differences are highly stable; however, the innovation levels of some peripherical cities improve. The growth of urban innovation levels show significant regional differences, with fast-growing cities clustered in the core area, and high-value areas characterized by proximity diffusion. Based on the innovation level in different periods, cities are divided into low–low, low–high, high–low, and high–high types. There are spatio–temporal differences in the driving factors for innovation. On the one hand, different periods show an intensification of factor inputs and external linkage effects, as well as the differentiation of urban development state effects. On the other hand, there are differences among different types of cities, with low–low cities mainly driven by factor inputs, urban development state, and internal opening-up; low–high and high–high cities are greatly influenced by factor inputs and urban development state. By expanding on existing studies, the present research provides a refined reference for the formulation of scientific policies aimed at promoting innovation development in China.

Keywords: innovation; spatio–temporal pattern; driving factor; regional difference; the Yangtze River Delta

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1. Introduction

Innovation is an important driver of regional development in the era of the knowledge economy, and improving the level of innovation has always been a core element of innovation geography research [1–3]. The endogenous growth theory, experiences of developed countries, and empirical studies show that with improvements in economic development, the "latecomer advantage" of under-developed economies is significantly weakened, and innovation becomes a new driver for economic growth and catch-up, with a weak innovation capacity likely causing social development to fall into a "middle-income trap" [1,4,5].

As the world's largest developing country, China's economic development has long been characterized by crude development, with high inputs and low outputs, resulting in a situation of weak industrial competitiveness [3]. In recent years, as China's economy entered the stage of high-quality development, the long-term quantitative growth model is no longer suitable for the needs of economic development. The shift from factor-driven to innovation-driven development has become an inevitable path for the transformation of economic growth kinetic energy, and for overcoming the middle-income trap [3,6,7]. As the importance of innovation gradually emerged, a series of policies aimed at promoting urban innovation development were developed from central to local governments. Many empirical studies find that relevant policies play a positive role, but do not eliminate significant regional disparities in China's innovation development [8,9]. However, the significant differences in, and irrational spatial organization of, innovation bring about problems, such as the inefficient allocation of innovation resources and the widening regional differences, severely restricting the development of regional innovation and the construction of a national innovation system in China [2,6,10]. Therefore, in the process of relying on innovation to achieve high-quality development in China, it is not only necessary to strengthen innovation investment, but more importantly, to narrow the regional innovation development gap, and then optimize resource allocation, improve innovation coordination, and achieve rapid development of regional innovation [4,11].

Currently, urban agglomerations are not only the regions with concentrations of innovation factors and important vehicles of national participation in global competition, but also the regions with the most frequent innovation interactions, and the most complex spatio–temporal pattern evolution and innovation systems in urban agglomerations that garnered extensive attention from scholars [12]. For China, urban agglomeration is an important vehicle for building an innovative country [7,13]. In the present research, taking the Yangtze River Delta (YRD), the most economically developed region in China with a high concentration of innovation resources, as a case study area, factors driving the innovation development in the YRD are explored, based on an analysis of the spatio–temporal evolution of innovation from the perspectives of innovation level and innovation growth, followed by a comparative spatial study based on the classification of realistic development conditions. Similar to existing research, this paper focuses on regional differences in innovation development in the YRD, and verifies the spatio–temporal heterogeneity of driving factors. Compared with related research, the possible innovations of this paper are as follows: on the one hand, accurate identification of the driving factors is an important foundation for promoting urban innovation development. The research on the driving factors based on the knowledge production function has a strong scientific character. On the other hand, based on the evolutionary characteristics of urban innovation development, the division method of urban types is proposed and as the basis for spatio–temporal evolution and driver identification. The relevant conclusions are more in line with the development reality of the YRD [9]. This study takes the YRD as an example to conduct a multi-faceted study, which not only enriches the existing research on the evolution of innovation patterns, but also provides a scientific reference for refining policy formulation.

2. Literature and Research Framework

Under the background of the new round of global industrial revolution driven by innovation, it has become a social consensus to improve the level of urban innovation development. From the perspective of theory guiding practice, solving this problem requires answering two questions: (1) What is the regional innovation pattern and its evolution characteristic? (2) What are the driving factors for innovation development?

Since Schumpeter introduced innovation into the economic growth theory, scholars conducted in-depth discussions on the evolution patterns and driving factors based on relevant theories [1,14,15], finding that there is a strong spatial concentration of innovation, which promotes economic and social development by improving resource utilization efficiency and optimizing industrial structure, and factor inputs, industrial structure, and innovation environment, which are all important factors that influence innovation development [10,14–16]. With the introduction of frontier theories, and the improvement of statistical data, scholars conducted in-depth studies on the evolution patterns and driving factors in multiple regions and at different scales [8,13,17]. The evolution of spatio–temporal patterns from multiple perspectives verifies the regional differences in innovation development. Using single or composite innovation indicators [2,3,17] and based on methods such as location quotient, the Gini coefficient, the relative development rate, and kernel density [8,11,18], many studies reveal that innovations in different regions, and on different scales, in China exhibit spatial concentration and significant regional differences [2,17]. Based on social network analysis, spatial interaction models, and gravity models [13,17,19], many studies highlight that, with the transformation of the innovation network from a single centre to multiple centres, China's innovation network strengthened, but the "core–periphery" difference in innovation linkages have not changed significantly [13,19]. Using data envelopment analysis and the Malmquist index model [9,20], many studies find that, from an "input–output" perspective, China's innovation efficiency is generally low, and there are significant regional differences, such as a "T-shaped" pattern at the national level, and a stepwise decreasing trend from eastern, through central, to western China [9]. Considering the emergence of the importance of innovation to economic and social development, the coordination of innovation with financial development [5] and economic growth [21] is explored, revealing that there is also a significant regional difference in the level of coordination, and that highly coordinated regions are mostly economically developed [21]. In a study of driving factors, scholars use qualitative analysis [4], or quantitative methods such as multiple linear regression [22], panel cointegration [11], geographically weighted regression [8], and generalized method of moments estimation [20], to find that innovation development is driven by factors such as factor inputs, macro policies, opening-up, industrial structure, and infrastructure [2,8,18,22]. However, there are differences in the effects of different factors, as well as in driving factors on different scales (e.g., provinces and cities), and in different periods in the same region [6,22].

Studies show that innovation is a dynamic and complex evolutionary process. On the one hand, the "cumulative effect" of the concentration of innovation factors in developed regions, under the effect of increasing returns to scale, brings about a widening in regional differences. On the other hand, innovation factor spillover and the latecomer advantage drive the narrowing of the gap in regional innovation development. That is, in the game of the distribution mechanism of innovation elements, the innovation pattern exhibits complex evolution in both the spatial and temporal dimensions [9,17,22]. In fact, the exploration of the spatial and temporal differences in innovation patterns has always been a focus of relevant studies [8]. For example, the urban innovation patterns in China shifted from polarized growth to balanced development [17]; regional comparisons reveal that the single-core driver evolved to multicore resonance in Shanghai, which differs from Beijing, where the single-core driver dominates [23]; in terms of driving factors, cities in the lower reaches of the Yangtze River Economic Belt are driven by economic development and government behaviour, while cities in the middle reaches are influenced by technology spillover, spatial location, government behaviour, and financial support [18]. Many studies verify the spatio–temporal differences in innovation [6,8,12], but there is also room for further improvement. More attention has been paid to comparisons of innovation patterns in different regions and their driving factors, with studies involving spatio–temporal comparisons of driving factors within a single region relatively lacking. The regional classification in spatial comparisons is mainly based on spatial location and administrative division [9,18], and spatial classification is rarely carried out from the perspective of actual development. For example, scholars classify Chinese provinces into four categories, i.e., science and technology (S&T) innovation-leading region, S&T breakthrough region, S&T improvement region, and S&T catch-up region, based on the dimensions of input scale and innovation efficiency, but no comparative study has been conducted on different types of driving factors [9]. With the implementation of China's innovation-driven strategy, the spatio–temporal pattern of innovation is characterized by a complex evolution. It is urgent to explore the evolution of regional innovation, and its driving factors, from spatio–temporal perspectives, the core focus of the present research, and an important supplement to existing research.

The spatio–temporal heterogeneity of regional innovation development is the consensus of current relevant research [4,5,10]. Facing this complex phenomenon, how to scientifically classify relevant cities is not only the basis for optimal policy formulation, but also the core issue discussed in this paper. To supplement this problem, this paper constructed the following analytical framework on the base of existing researches (Figure 1). First, the evolutionary trend of innovation patterns in the YRD was studied by combining the coefficient of variation and the locational Gini coefficient to verify the overall status of the innovation gap. Second, we conducted a comparative spatio–temporal study of the evolutionary patterns of urban innovation levels. On this basis, the relative development rate index was used to analyze the factors inherent of the pattern evolution characteristics. Thirdly, the classical knowledge production function was introduced into the study of drivers, and a comparative analysis of drivers in different periods was conducted. Finally, we conducted further discussions based on relevant research, including city classification and innovation development orientation based on relative development rate index, the identification and comparison of innovation development drivers in different types of cities, and how to better guide urban innovation development in the future.

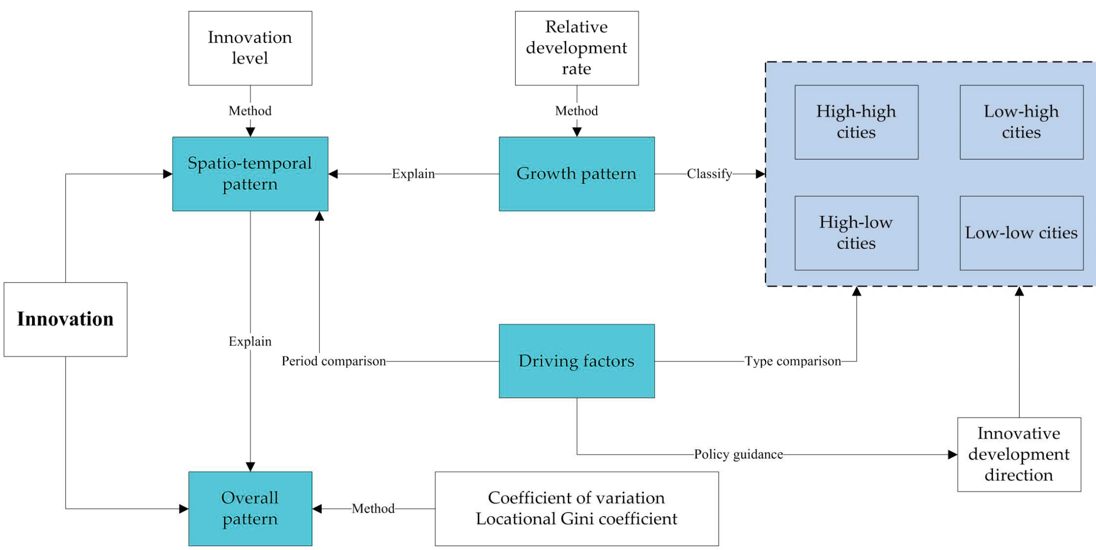

Figure 1. The basic research framework.

3. Study Area, Methods and Data

3.1. Study Area

Since the reform and opening-up, urban agglomeration has increasingly become an important spatial form of urban organization in China, as well as an important vehicle for promoting regional integration development and narrowing regional development gaps. In particular, the YRD urban agglomeration (Figure 2), located on the eastern coast of China, as a typical natural plains region, gradually transformed from a physical geographical area to an economic region, and the multi-level and wide-ranging cooperation mechanism among cities increasingly improved under the impetus of multiple actors, such as government, academia, and enterprises. Since the 1990s, relying on an integrated cooperation system, the status of urban agglomerations was significantly enhanced by the gradual transformation of single to integrated development of cities, as well as by the expansion of the spatial scope of urban agglomerations. In recent years, the economic and social development of the YRD became a focus of scholars. Although the definitions of the scope of urban agglomerations differ among scholars [7,12], they all reflect the necessity of relying on urban agglomeration to promote regional development.

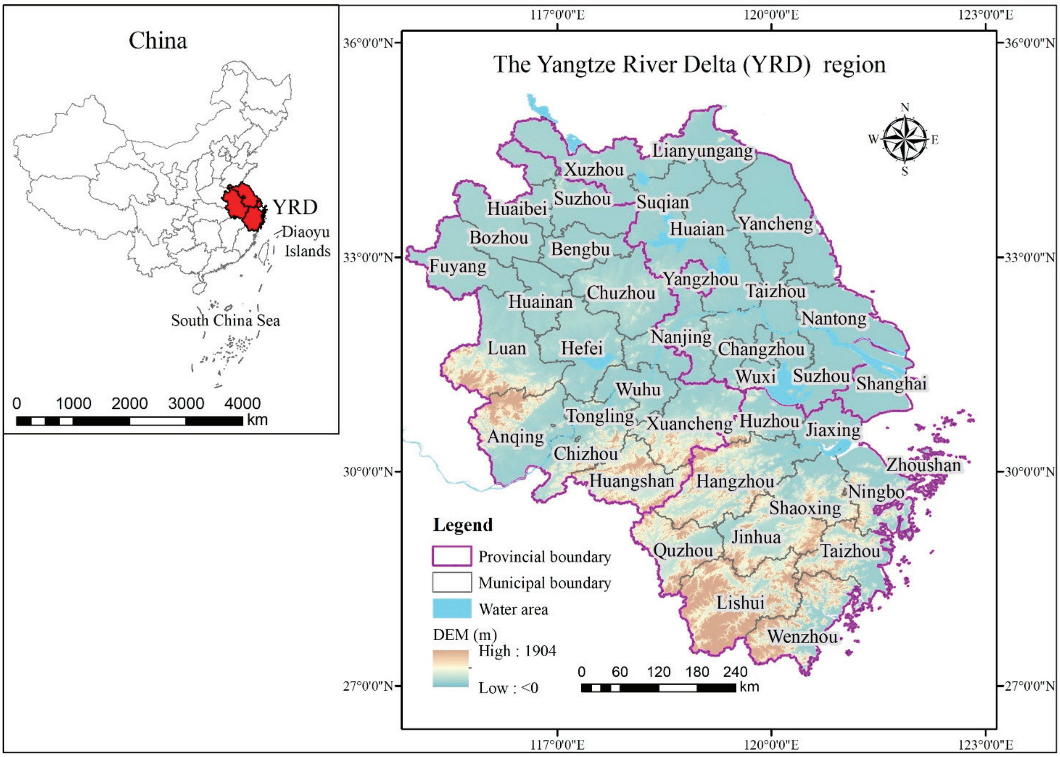

Figure 2. Location map and administrative division of the YRD.

On 5 November 2018, at the opening ceremony of the First China International Import Expo held in Shanghai, China, the president of Chinese, Xi Jinping, mentioned in his keynote speech that China would support regional integration development of the YRD, and upgrade such developments to a national strategy, which enhances the urban agglomeration strategic position while further imposing higher requirements for the development. Subsequently, the Central Committee of the Communist Party of China and the State Council issued the outline for the Yangtze River Delta Regional Integration Development Plan, which specifies the scope of the YRD as the entire region of Shanghai, Jiangsu, Zhejiang, and Anhui; this document is also an important basis for selecting the scope of the present research. In general, the YRD, known as China's "Golden Triangle", is one of the regions with the most active economic development, the highest degree of opening-up, and the strongest innovation capacity in China, and has a pivotal strategic position in national modernization and all-round opening up. In 2018, the YRD had a GDP of approximately CNY 21.15 trillion, and a resident population of 225 million, accounting for 23.12% of the GDP and carrying 16.15% of the population, with a land area accounting for approximately 3.74% of China, showing a significantly high concentration of factors. In the future, with the emergence of the importance of innovation development, and the accelerated implementation of China's urban agglomeration strategy, the YRD will play a vital leading role in the construction of China as an innovative country, and its "core–periphery" differences in regional innovation development are also highly representative.

3.2. Research Methods for Analyzing Spatio–Temporal Pattern of Innovation

The scientific measurement of innovation level is the key basis for subsequent research. Currently, single indicators and composite indicators are used in academia to measure innovation level [18]. The former include S&T research articles, the output value of new products, and patents [22,24], while the latter include factors such as knowledge, and innovation base for composite measurements [4]. Due to the differences in the determination of new products in different regions, and the limited S&T research articles [24], there are issues with regard to repeated calculations and difficulty in obtaining long time-series data for composite indicators. In comparison, patents are advantageous because they are generated using unified identification standards and provide good data availability [3], and, thus, have become a common indicator of innovation level in existing studies [7,12]. Under the patent "application-review" system in China, patents granted can better characterize the actual output of innovation than patent applications [7].

(1) Coefficient of variation (*CV*) and locational Gini coefficient (G). A variety of methods, such as the *CV*, the Gini coefficient, the entropy index, and the Herfindahl–Hirschman Index (HHI), are proposed in the study of spatial characteristics of regional innovation [18,24]. Referring to existing studies, the present research selects the *CV* and the locational Gini coefficient to measure the overall pattern of innovation development in the YRD. Specifically, the *CV*, also known as the standard deviation rate, or the coefficient of dispersion, is the ratio of the standard deviation to the mean. As a statistic to measure the degree of variation in observed values, the *CV* reflects the relative equilibrium of innovation development in urban agglomerations [14]. *CV* is calculated as follows:

$$CV = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{x})^2}{n}} / \overline{x} \tag{1}$$

where n is the number of study units, x_i is the innovation status of city I, and $\overline{x}$ is the mean of the innovation status of the urban agglomeration. Overall, the smaller the *CV*, the more balanced the regional innovation pattern, and conversely, the larger the *CV*, the more significant the regional differences.

Unlike the *CV*, the locational Gini coefficient is more mathematically conceived, simple, and fast to calculate, and uses the most readily available data to measure the degree of innovation concentration in an urban agglomeration [18]. For this reason, the locational Gini coefficient (*G*) is adopted in the present research to measure the degree of innovation concentration in the geographical space, and it is calculated as follows:

$$G = \frac{1}{2n^2\overline{x}} \sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j| \tag{2}$$

where n represents the number of study units, $\overline{x}$ represents the mean of the innovation status of the urban agglomeration, and x_i and x_j represent the innovation status of cities i and j, respectively. The larger the locational Gini coefficient, the stronger the regional innovation imbalance, and the higher the degree of geographical concentration of innovation.

(2) Relative development rate index (*NICH*). The *NICH* index intuitively characterizes the innovation development rate of a city relative to an urban agglomeration in a certain period of time [4,8]. It is calculated as follows:

$$NICH = \frac{Y_{2i} - Y_{1i}}{Y_2 - Y_1} \tag{3}$$

where Y_{1i} and Y_{2i} denote the innovation status of city i at the beginning and end of a certain period, respectively; and Y_1 and Y_2 represent the innovation status of the urban agglomeration at the beginning and the end of a certain period, respectively.

3.3. Research Methodology for Innovation Driving Factors

An accurate understanding of the driving factors of innovation development is an important basis for formulating scientific policies to guide the balanced implementation of factors, and improve the innovation level of urban agglomerations. Based on agglomeration theory, innovation systems theory, and evolutionary economic geography [2,23], scholars obtained a multitude of results using qualitative analysis and quantitative research [18,25]. The driving factors for innovation as a dynamic process of knowledge production have been studied from multiple perspectives, and diverse models proposed [3,22]. Among them, the knowledge production function (KPF), which is proposed on the basis of the economic growth model, is commonly used in innovation research [26,27]. Based on the KPF and drawing on existing studies [26], this research classifies the driving factors into three categories: factor inputs, development status, and external linkage. On this basis, the following econometric model is constructed:

$$Y = A \cdot {X_1}^{\alpha} \cdot {X_2}^{\beta} \cdot {X_3}^{\gamma} \cdot \varepsilon \tag{4}$$

where Y is the urban innovation output; X_1, X_2, and X_3 are factor input, urban development state, and external linkage factors, respectively; A is a constant; α, β, and γ are elasticity coefficients; and ε is the random error.

To further eliminate the effect of heteroscedasticity, the logarithm of both sides of Equation (4) is taken to obtain the following regression model:

$$\ln Y = \ln A + \alpha \ln X_1 + \beta \ln X_2 + \gamma \ln X_3 + \varepsilon \tag{5}$$

Based on the comprehensive consideration of the endogeneity and collinearity of variables, in conjunction with data availability, relevant indicators are selected and measured as follows:

(1) Factor inputs. As a complex knowledge production process, factor inputs are the basis of innovation outputs, and mainly include human input and capital input [27,28]. The total number of employees in scientific research and technical services (unit: person) is used to reflect the status of urban talent input (*Tal*), and the scale of expenditure on S&T and education (unit: CNY 100 million) is used to reflect the intensity of urban innovation input (*Fund*);
(2) Urban development state. Industry is the subject of urban innovation development, and the added value of secondary industry (unit: CNY 100 million) is used as an indicator for the urban industrial scale (*Ind*). The level of financial development effectively drives urban innovation development, by lowering the threshold of innovation, improving financing constraints, and increasing the local technology absorption capacity [13,29]. The financial institution loan balance of the city at the end of the year (unit: CNY 100 million) is used to characterize the financial development level of the city (*Fin*);
(3) External linkage. Improving transportation facilitates the transformation of local innovation resources and the promotion of resource sharing between cities [7]. City passenger volume (unit: 10,000 person-times) is used to characterize urban traffic conditions (*Tra*). Market guidance, the competition effect, and the crowding-out effect brought by opening-up, and the higher technology spillover from foreign enterprises, talent competition, and global mergers and acquisitions, all have an impact on the innovation development of Chinese cities [4,27]. The total amount of foreign capital actually utilized (unit: CNY 100 million) is selected to characterize the level of urban openness (*Ope*).

3.4. Research Data

The study period of the present research is from 2000 to 2018. Considering that prefecture-level cities, which are an important support for the implementation of regional development strategies and national macroeconomic policies, play key roles in economic development, this study uses cities as the basic units for the study. However, it must be emphasized that the administrative divisions of the YRD underwent major adjustments during the study period. For example, Chaohu, a prefecture-level city in Anhui Province, was abolished in 2010, and one district and four counties originally under the jurisdiction of Chaohu were transferred to the cities of Hefei, Wuhu, and Ma'anshan, after which a series of administrative divisions in Anhui were adjusted. Therefore, to obtain robust research findings, it is necessary to select a suitable administrative division as the research benchmark. Considering data availability, the present research uses the administrative division in 2010 as the benchmark.

The relevant data in this study were obtained from provincial and municipal statistical yearbooks, as well as city statistical yearbooks and statistical bulletins from 2000 to 2019. The data were processed as follows: (1) data from cities involving zoning adjustments are estimated with county-level data; (2) economic data are based on the year 2000, and adjusted with relevant price indices; and (3) some missing or adjusted data are estimated, based on the average growth rate for previous years.

4. Results

4.1. Overall Trend of Innovation Level Evolution

The innovation level of the YRD is calculated based on granted patent data, and the evolution characteristics of the innovation pattern are analyzed using Equations (1) and (2) (Figure 3). From 2000 to 2018, the number of granted patents increases from 19,500 to 763,800, and the number of patents granted per 10,000 people increases from 0.99 to 33.89, indicating significant improvement in the innovation level. Both the CV and G, based on the number of patents granted per 10,000 people, show significant decreasing trends; in particular, there is a rapid increase in the number of patents in Jiangsu, Zhejiang, and Anhui, driven by the active innovation of enterprises and improvements in innovation platforms in recent years, which is an important force in promoting the transformation of innovation patterns [27]. The comparison reveals that there are differences in the spatial evolution among different periods. Specifically, between 2000 and 2008, the urban innovation level steadily increases, and the spatial difference fluctuates down, showing a significant trend of running at a high level. Since 2009, the innovation level fluctuates up, and the regional difference steadily decreases, with a relatively small overall difference and fluctuation range. In particular, since 2014, the fluctuating growth in innovation level and the stability of regional differences obviously coexist. In general, in the context of the transformation development environments, as well as the acceleration of industrial transformation and transfer, the innovation level in the YRD significantly improves, along with the complex distribution of innovation resources [30], but the imbalance in innovation level significantly weakens.

4.2. Evolution Characteristics of the Spatial Pattern of Innovation

Since the beginning of the 21st century, national strategic support, enhanced innovation input, and an optimized industrial structure brought about a rapid rise in innovation development; however, this cannot conceal significant regional differences. To eliminate the influence of city size, the number of patents granted per 10,000 people is used as an indicator to characterize the level of urban innovation. Based on the threshold values of 1.75, 1.25, 0.75, and 0.25 times the innovation level of urban agglomeration [22,24], the cities are classified into five categories: high, medium high, medium, medium low, and low. The spatio–temporal pattern evolution of innovation in different periods (2015, 2008, and 2018) is compared (Figure 4).

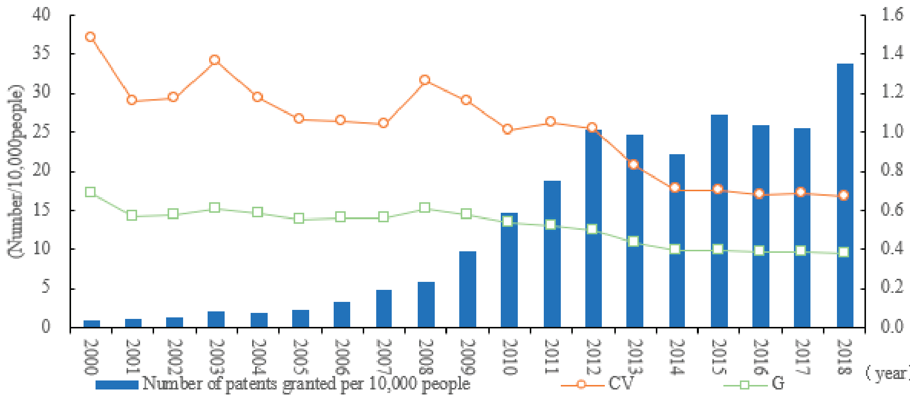

Figure 3. Overall evolution of innovation in the YRD from 2000 to 2018.

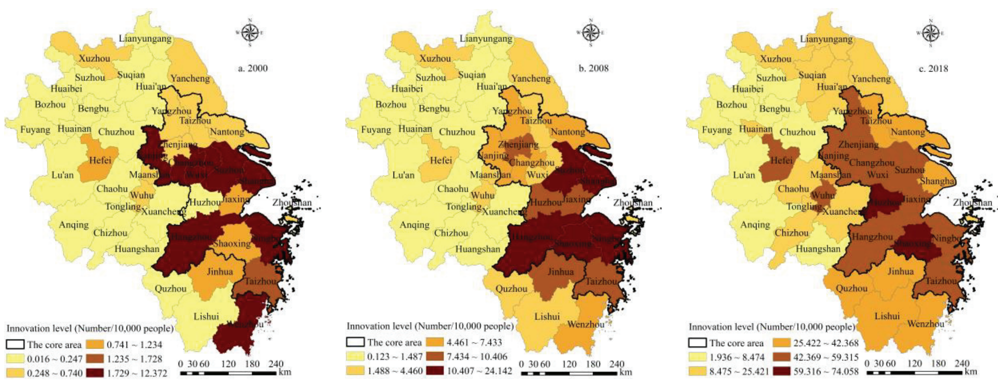

Figure 4. Evolution of the spatial and temporal patterns of innovation in the YRD from 2000 to 2018.

In the follow-up research, we will see many comparative studies using 2008 as a cut-off point. Therefore, it is necessary to explain the considerations that led us to make this choice. For China, urban development is not only regulated by national macro policies, but is also closely related to the global development environment. For example, many studies identify the opening-up to the outside world as an important driver of economic growth and innovative development in Chinese cities [3,18]. On the one hand, the impact of the global financial crisis in 2008 made more and more cities recognize the importance of innovation development as an endogenous driving force for regional economic growth. On the other hand, the "Guiding Opinions on Further Promoting Reform and Opening Up and Socioeconomic Development in the Yangtze River Delta Region", promulgated by the State Council in 2008, indicate that regional development entered the national macro strategy, which promotes the integration development process of urban agglomerations. The empirical research used in this paper also finds that the regional innovation development pattern changes under the impetus of macro policies and the impact of the global financial crisis since 2008 (Figure 3). Therefore, the comparative study with 2008 as the cut-off point has a certain practical feasibility. The results are as follows:

(1) In 2000, there are 8 high-level cities and 20 low-level cities, with the former (except Wenzhou) distributed in the core area and concentrated around the Shanghai–Nanjing–Hangzhou–Ningbo axis, and the latter (except Huzhou) located in the peripheral area and clustered in Anhui and northern Jiangsu;

(2) In 2008, there are 5 high-level cities and 17 low-level cities. From 2000 to 2008, the former are concentrated around the Shanghai–Nanjing axis to the Shanghai–Hangzhou–Ningbo axis, and the latter are still clustered in Anhui and northern Jiangsu. From 2000 to 2008, the spatial evolution decreases in Nanjing, Changzhou, Wuxi, Wenzhou, and Hefei; and increases in Zhenjiang, Yangzhou, Nantong, Shaoxing, Jiaxing, Huzhou, Quzhou, and Lishui, with the former clustered in southern Jiangsu, and the latter dominated by cities in Zhejiang. This is the direct reason for the shift in the regional innovation axis from "Shanghai–Nanjing–Hangzhou–Ningbo" to "Shanghai–Hangzhou–Ningbo".

(3) In 2018, there are two high-level cities and nine low-level cities, with the former being Huzhou and Shaoxing, and the latter still distributed within Anhui; the decrease in the number of high-level and low-level cities, and the narrowing of the extreme differences in innovation levels, both confirm the narrowing of regional differences in innovation. From 2008 to 2018, the spatial evolution decreases in Shanghai, Suzhou, Hangzhou, Jinhua, and Ningbo, and increases in 19 cities including Nanjing, Suqian, Lianyungang, Hefei, and Huainan, but the spatial distribution differs significantly from that of 2000–2008, with the former dominated by cities along the Shanghai–Hangzhou–Ningbo axis, and the latter clustered around peripheral cities in Jiangsu and Anhui. This shift also explains the narrowing of the regional differences in innovation.

Overall, the spatio–temporal evolution of urban innovation level in the YRD is characterized as follows: (1) although the innovation level of some neighboring cities increases, "the core–edge" difference is still significant under the constraint of spatial dependence, i.e., there is spatial concentration and stability in the innovation pattern of urban agglomerations. (2) The north–south divergence in innovation levels is not only manifested within the scope of urban agglomerations, but also clearly exists in the core areas and some provinces, such as southern and northern Jiangsu, which indicates the diversity and complexity of innovation patterns in the YRD. (3) The innovation diffusion in high-value areas is characterized by distance proximity, and the "Z-shaped" belt along the Shanghai–Nanjing–Hangzhou–Ningbo axis is an innovation-active area in the YRD, and the center of diffusion to cities with high and medium-high innovation levels.

4.3. Evolution Characteristics of the Spatial Pattern of Innovative Growth

The differential growth of urban innovation levels under the combined effect of internal and external factors is a direct factor in the evolution of the spatial pattern of innovation in urban agglomerations [22]. Using the number of patents granted per 10,000 people as an indicator for the urban innovation level, the evolution of the spatial pattern of innovation growth in urban agglomerations is characterized (Figure 5) by calculating the NICH index (Equation (3)), and then classifying cities into four categories [24]. In the 2000–2018 period, there are regional differences and spatial steady-state characteristics of the NICH index results, for example, "core–periphery" differences and north–south differences, caused by generally high values in Zhejiang. Comparisons of the different periods reveal the following:

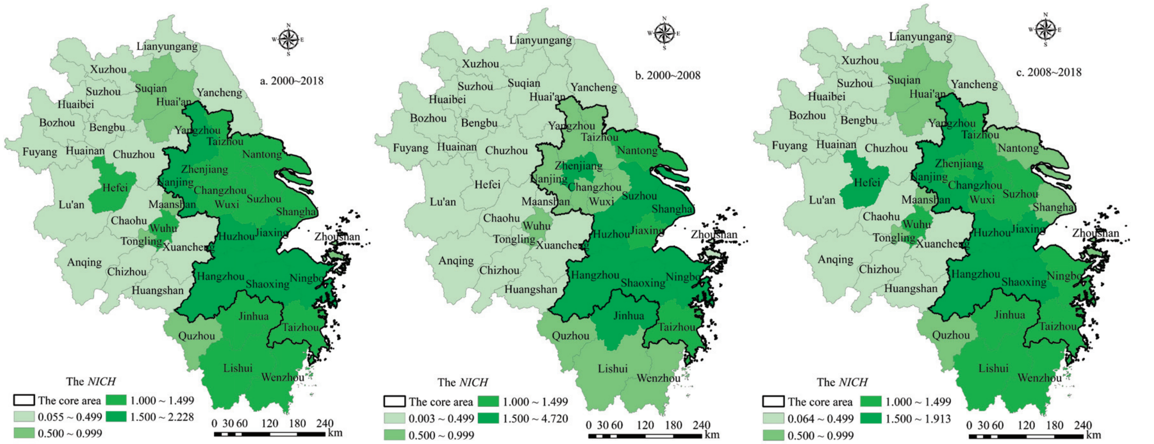

Figure 5. Evolution of innovation growth pattern in the YRD from 2000 to 2018.

(1) From 2000 to 2008, there are 22 low-growth cities, concentrated in Anhui and northern Jiangsu, and only 8 high-growth cities, which include Shanghai, Zhenjiang, Hangzhou, Ningbo, and Huzhou. The high-growth cities are also cities with high innovation levels, reflecting the "Matthew effect" of innovative development, a finding that is also confirmed by the high fluctuations in the *CV* and the *G*;

(2) In 2008–2018, while high-growth cities are concentrated in the core area, there are also cities in the peripheral area (for example, Hefei and Wuhu), and the low-growth cities are still clustered around the periphery. Compared to those in the 2000–2008 period, the growth rates for cities such as Nanjing, Wuxi, Hefei, Ma'anshan, and Wuhu increase substantially, and the growth rates for Shanghai, Ningbo, Shaoxing, and Jinhua decrease significantly, becoming a direct factor in driving the diffusion of innovation from core high-value areas to peripheral areas, and narrowing the regional differences.

From 2000 to 2018, high-growth and low-growth cities are clustered in the core and peripheral areas, respectively, with a stable "core–edge" difference in innovation growth, indicating that innovation resources are consistently concentrated in developed cities [11], becoming an important factor in the stability of innovation levels and innovation growth patterns. In particular, the innovation level and the NICH index are generally higher in Zhejiang cities, due to the more active private economy, and the more developed modern financial sector. For example, the establishment and improvement of innovation platforms, represented by the online technology market since 2002, fostered entrepreneurship and promoted the rapid development of innovation [27]. In addition, the spatial concentration of high-value areas (innovation and the NICH index) confirms the spatial concentration of innovation development.

4.4. Identification of Driving Factors for Innovation Development

Based on Equation (5), the driving factors for innovation development in the YRD are discussed from the perspective of the scale of innovation output. The correlation test [30] results indicate that the variance inflation factor (VIF) is 5.66, i.e., there is no multicollinearity between the variables, and the Hausman test results indicate that the fixed effects (FE) model should be selected. The regression results (Table 1) show that the increase in factor inputs, improvements in the urban development state, and the enhancement of external linkages all promote innovation development. Based on the evolutionary characteristics of the innovation patterns of urban agglomerations, and taking into account the comparability of different time periods and the balance of samples, the driving factors for innovation development in the 2000–2008 and 2009–2018 periods are comparatively studied. In general, the effect of driving factors varies among different periods under the development orientation and factors competition, indicating that policies for promoting innovation development should be formulated to "keep up with the times", as follows:

Table 1. Regression results for driving factors for innovation development in the YRD.

	2000–2018		2000–2008		2009–2018	
	FE	**RE**	**FE**	**RE**	**FE**	**RE**
Tal	0.301 *** (5.78)	0.163 *** (3.38)	0.0815 (1.04)	−0.0112 (−0.16)	0.298 *** (4.05)	0.403 *** (3.08)
Fund	0.0879 ** (2.05)	0.242 *** (6.49)	0.0386 (0.71)	0.0861 ** (2.01)	0.257 ** (2.20)	0.712 *** (8.71)
Ind	1.450 *** (11.61)	1.099 *** (10.76)	1.075 *** (6.42)	0.960 *** (7.10)	2.382 *** (11.65)	1.427 *** (11.74)
Fin	0.491 *** (7.27)	0.510 *** (7.49)	0.767 *** (5.48)	0.691 *** (5.62)	−0.399 (−0.86)	−0.231 (−1.07)
Tra	0.243 *** (4.81)	0.276 *** (6.08)	−0.0164 (−0.15)	−0.0527 (−0.61)	0.144 ** (2.14)	0.142 *** (2.70)
Ope	−0.0908 *** (−3.10)	−0.103 *** (−3.58)	−0.0986 ** (−2.42)	−0.0960 ** (−2.48)	0.138 *** (2.79)	0.0567 (1.35)
Constant	−0.853 *** (−3.72)	−0.168 (−0.72)	−0.0744 (−0.19)	0.391 (1.20)	0.106 *** (4.25)	0.103 *** (4.44)
R^2	0.924	0.920	0.743	0.740	0.782	0.765
Hausman	104.42 ***		14.02 **		61.72 ***	

Note: **, and *** indicate significance levels of 0.05, and 0.01, respectively, and t-statistics are in parentheses.

(1) Factor inputs. Through qualitative and quantitative evolution, innovation factor inputs have differentiated effects in different periods, and show a shift from a non-significant positive effect to a significant positive effect. The non-significant factor input-driven effect from 2000 to 2008 is related to the low efficiency of factors in the low-level innovation stage. In the economic growth process under GDP competition, innovation is not the focus of development in all cities, and innovation resources are concentrated in a few cities, such as Shanghai, Nanjing, and Hangzhou. Due to institutional mechanisms and the market environment, factor input growth exhibits a "Solow paradox" because of low human labor skills and a non-optimized infrastructure, explaining the non-significant correlation [27]. From 2009 to 2018, as the global development environment changes and the comparative advantages of urban agglomeration elements change, more and more cities realize the importance of innovation. Improvements in talent and increases in capital input in the process of urban development increasingly become the core drivers of innovation development, by enriching the knowledge pool, mobilizing high-end innovative talents, and optimizing innovation policies. However, under the "Matthew effect" mechanism of factor distribution, the concentration of innovative talent in the core area, and strong capital input in developed cities, become important factors for the stability of the "core–periphery" differences in innovation development;

(2) Urban development state. In the process of economic and social development, the degree of coupling between the level of urban development and the demand for innovation is an important factor affecting innovation efficiency [5,21]. The development of the manufacturing industry, as an important innovation subject, promotes improvements in urban innovation, with the enhancement of innovation capacity and competitiveness brought by industrial transformation and upgrading. Export-

oriented low-end development of industry during rapid economic growth in the 2000–2008 period is an important reason for the relative weakness of this effect. From 2009 to 2018, the innovation level of enterprises increases significantly and promotes the development of urban innovation under market demand, government guidance, and urban development enhancement. Financial development can reduce the risk and cost of innovation for enterprises, and promote urban innovation development. However, as the quality of innovation improves, the financial development of traditional businesses cannot meet the demand of higher-end innovation (e.g., original innovation); the high cost and capital redundancy of traditional finance in China may be one of the factors leading to the negative effect from 2009 to 2018 [20,29]. In addition, the strengthening of inter-city financial ties and cross-regional venture capital through deepening integration are among the important driving factors for this shift and regional innovation differences [20]. In the future, improving the level of industrial development, and vigorously developing modern finance, will become important measures to promote the development of urban innovation;

(3) External linkage. The spillover effect and the Matthew effect are important driving mechanisms for the evolution of innovation patterns in urban agglomerations, with the former manifesting as innovation synergy through the sharing of innovation resources and gradient transfer of factors, and the latter emphasizing that the spatial concentration and path dependence of innovation factors further concentrate innovation resources and widen the innovation level gap. Urban innovation is driven by factor distribution, knowledge diffusion, and city competition and cooperation within urban agglomerations, but urban innovation resources also faces the risk of "siphoning" [13,17]. The traffic effect changes from a negative effect to a significant positive effect, indicating a strong "Matthew effect" of innovation factors in the 2000–2008 period, i.e., improvements in the transportation accessibility of the most under-developed cities is accompanied by the siphoning off of innovation factors. From 2009 to 2018, with improvements in high-level transportation networks, such as high-speed rail, and changes in regional macroeconomic policies, the strengthening of inter-city cooperation brings about a significant increase in the exchange of innovative talents and the spillover effect of innovation, for example, the frequent flow of innovative talent among cities, entrepreneurship, and job-hopping, which enhances the efficiency of resources, and promotes the collaborative development of innovation in regional interaction and exchange [28]. The advanced management and cutting-edge innovations brought by multinational corporations are important drivers of imitative innovation by local firms; however, foreign investors also inhibit the innovation of local firms, through resource competition and mergers, to maintain their global competitive advantage [4,22,27]. This effect is significantly negative in the 2000–2008 period, indicating that factor competition, and the innovation inhibition effect, in the process of foreign capital concentration, are more significant, and that the weak learning and absorptive capacity, due to the low-level of urban innovation, is an important factor. The significant positive effect in the 2009–2018 period is driven by improvements in urban innovation, the deepening of regional opening patterns, and the increase in innovation capacity brought by high-end foreign investment. In recent years, the deepening of China's internal and external opening-up, as well as the increasing degree of integration of cities into the global production network, are important driving factors for innovation development in under-developed cities.

5. Discussion

5.1. City Classification Based on the Evolution of Innovation Growth

Under the combined effect of internal and external factors, the change in the innovation pattern in the YRD from 2000 to 2018 do not significantly change the "core–periphery" differences in innovation development. The core area, especially the cities along the G60 (an innovation collaboration region initiated by Shanghai that passes through the cities of

Shanghai, Jiaxing, Hangzhou, Jinhua, Suzhou, Huzhou, Xuancheng, Wuhu, and Hefei), dominate innovation growth among urban agglomerations, and the spatio–temporal evolution shows an acceleration of the relative growth of some cities in southern and central Jiangsu. The uneven innovation level among urban agglomerations is an important manifestation and key driver of urban development differences, and balancing innovation patterns become a key measure to achieve high-quality development. Additionally, the complex evolutionary patterns of urban innovation also require differentiated policy formulation. In this regard, this section divides the cities into four categories, based on the NICH index (Figure 6), and proposes the main directions of innovation development for each category of cities, from the perspective of regional coordination.

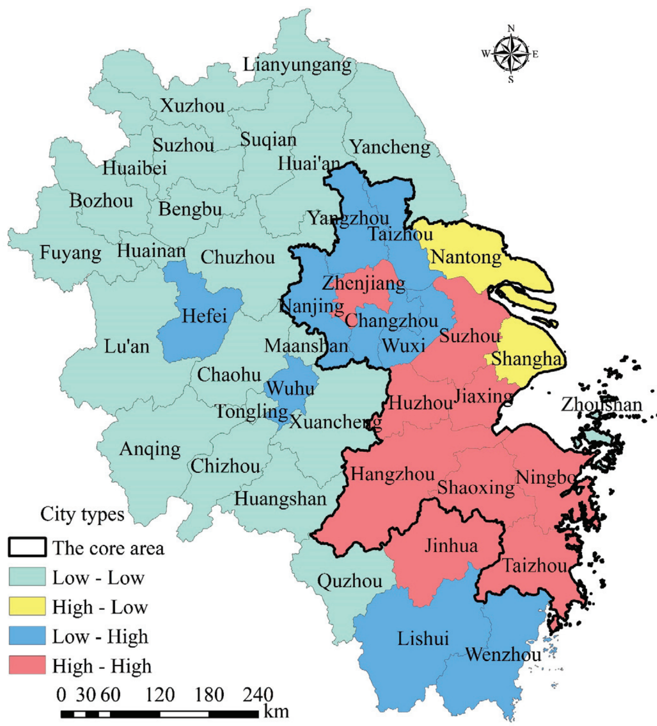

Figure 6. Cities with different types of innovation growth in the YRD.

(1) High–high cities. Cities of this type have a NICH index greater than 1.00 in both periods and, thus, significantly high urban innovation growth capacity; this group includes eight core-area cities (e.g., Hangzhou, Ningbo, Suzhou, and Zhenjiang) and one non-core area city (Jinhua), which are mainly in Zhejiang. However, with innovation transformation and industrial migration, the NICH index declines for most cities. A developed economy, superior infrastructure, and a concentration of innovative resources are important drivers for rapid innovation development, but the quality of such innovation requires further improvement (e.g., the proportion of invention patents granted in Zhejiang is only 11.44% in 2018, significantly lower than that in Shanghai (23.07%)). In the future, transformation to higher-quality innovation, improvements in the level of industries, both independent and controllable, and the realization of more competitive innovation development will become important directions for promoting high-quality economic development;

(2) High–low cities. Cities of this type have a NICH index greater than 1.00 in the 2000–2008 period, and less than 1.00 in the 2008–2018 period; this group includes

Shanghai and Nantong, with the NICH index of the former decreasing significantly, and that of the latter remaining stable. The innovation in Shanghai is characterized by "high input and slow output". The transformation from practical innovation to original innovation, coupled with an increase in factor costs and the acceleration of industrial transfer leading to the out-migration of some industries, becomes an important factor for the significant decline in the NICH index [27]. The development of urban innovation is comprehensively influenced by factor inputs and inter-city interactions. The significant "siphoning effect" of cities such as Shanghai on innovation resources is a key factor for the decline in the NICH index in Nantong. For these cities, an important future direction is to explore the path of industrial transformation and high-quality innovation based on their own foundations, and by participating in urban agglomeration innovation integration, so as to provide a reference for other cities in the process of innovation development and industrial transformation;

(3) Low–high cities. Cities of this type have a NICH index less than 1.00 in the 2000–2008 period, and greater than 1.00 in the 2008–2018 period; this group includes five core-area cities (e.g., Nanjing, Taizhou, and Yangzhou) and four peripheral area cities (e.g., Hefei and Lishui). In terms of time comparisons, driven by the increase in endogenous power, the modernization of southern Jiangsu and the government-led innovation inputs in Hefei accelerate, and, therefore, the NICH index of the cities in Jiangsu and Hefei increases significantly; the other cities rely on their location and cost advantages and, through industrial transfer and innovation spillover from developed cities, achieve innovation growth, but their NICH index values increase relatively little. In the process of integration, for these cities, urban innovation development should include taking advantage of their superior location and policies to utilize innovation factors and lead innovation networks to achieve innovation improvements and structural optimization, while driving the innovation development of surrounding areas;

(4) Low–low cities. Cities of this type have a NICH index of less than 1.00 in both periods, and, thus, have weak urban innovation growth; this group includes 21 peripheral area cities (e.g., Anqing, Huai'an, and Quzhou) and 1 core area city (Zhoushan). An important reason for the relatively slow innovation growth is the strong concentration of innovation factors in the YRD, influenced by the low level of development, and the strong "siphoning effect" of innovation factors in developed cities. Sustained low-level innovation is not conducive to urban economic growth or the narrowing of the development gap in urban agglomerations. In the future, these cities should optimize their innovation environment, take advantage of the innovation spillover effect of developed cities in the core area, actively promote industries that meet their needs, and strengthen the level of coordinated innovation with developed cities to achieve high-quality development.

5.2. Comparative Study on the Driving Factors for Different Types of Cities

There are significant differences in the innovation development and evolution of different cities in the YRD, a finding that poses higher requirements for the future formulation of policies aimed at improving the innovation development of urban agglomerations, especially highlighting the urgent relevance of guiding urban innovation development "based on local conditions". The "precise implementation of policies" that drives innovation development in urban agglomerations requires the identification of the driving factors for innovation development in different types of cities. Based on the city classification results in Section 4.1, a comparative study of the driving factors for innovation development in low–low, low–high, and high–high cities was conducted, based on the sample size and the corresponding robustness of the results (Table 2). The Hausman test results indicate that the FE model is the most appropriate, and that there are differences in the driving factors for innovation development in different types of cities, as follows:

Table 2. Regression results for driving factors for innovation development in different types of cities.

	Low–Low Cities		Low–High Cities		High–High Cities	
	FE	**RE**	**FE**	**RE**	**FE**	**RE**
Tal	0.359 *** (4.92)	0.235 *** (3.15)	0.386 *** (2.91)	0.0874 (0.91)	0.212 * (1.95)	−0.0263 (−0.31)
Fund	0.340 *** (5.53)	0.0517 (0.79)	0.231 *** (2.86)	0.0235 (0.24)	0.278 *** (3.28)	0.107 (0.92)
Ind	1.495 *** (8.15)	0.723 *** (5.04)	1.805 *** (6.57)	1.703 *** (7.91)	1.868 *** (5.40)	1.143 *** (6.03)
Fin	0.320 *** (3.34)	0.511 *** (4.84)	0.359 ** (2.26)	0.261 * (1.84)	0.586 *** (3.20)	0.622 *** (4.04)
Tra	0.466 *** (6.89)	0.321 *** (4.63)	0.00121 (0.01)	0.0714 (0.76)	−0.471 *** (−3.40)	−0.332 ** (−2.55)
Ope	−0.0920 ** (−2.28)	−0.0272 (−0.62)	−0.0616 (−0.83)	−0.275 *** (−4.45)	−0.121 (−1.59)	−0.227 *** (−4.36)
Constant	−1.535 *** (−5.00)	0.0290 (0.09)	−0.585 (−1.13)	0.290 (0.62)	1.215 * (1.70)	1.900 *** (3.22)
R^2	0.925	0.915	0.939	0.931	0.937	0.933
Hausman	120.64 ***		34.10 ***		24.14 ***	

Note: *, **, and *** indicate significance levels of 0.1, 0.05, and 0.01, respectively, and t-statistics are in parentheses.

(1) Factor inputs show positive effects in different regions, but there is also regional heterogeneity. The more developed a city is, the more significant the importance of innovation in economic growth is, and the higher the skill requirements for innovative talents. The strong innovation capacity and weak driving effect in high–high cities indicate that in urban innovation development, the marginal effect of increasing the quantity of innovative talent decreases, while improving the quality of talent becomes an important measure to accelerate urban innovation development. Capital input promotes urban innovation development. However, low–low cities with a low innovation level still have incomplete innovation facilities, and have the highest capital efficiency in the rapid development of innovation. For low–high and high–high cities with relatively small differences in innovation levels and capital input intensity, the difference in the capital input effect is related to market, government powers, and differences in industrial structures. Specifically, low–high cities with obvious government drive require higher government investment and input in innovation facilities, and the marginal effect of capital input slows during the stage involving the enhancement of human capital and gradual improvements in innovation facilities. High–high cities, mainly in Zhejiang, are dominated by small and medium-sized enterprises, and low–high cities are dominated by large manufacturing industries; the difference in innovation subjects and the gap between government–enterprise collaboration are the factors that bring about short-term differences in the effects;

(2) Improvements in urban development promote the innovation development of all cities, but the higher the innovation level, the stronger the effect. From the perspective of industrial structure, the higher the urban innovation level, the more significant the effect, indicating that, with improvements in urban development and the transformation of the industrial structure, the innovation level of industrial enterprises also significantly improves. Developed and complete financing provides sufficient financial support for innovation, and improvements in financial development are conducive to improving financing constraints, further boosting the efficiency of financial capital in innovation development, and providing strong support for optimizing urban innovation environments [5]. A regional comparison reveals that the coordinated development of a better innovation foundation and high-end service industries

in low–high and high–high cities has a more significant driving effect on urban innovation development. In general, the development of the manufacturing industry promotes urban innovation through scale growth and structural optimization, and the development of service industries (e.g., finance) drives innovation development by improving the innovation environment and providing convenient services [29], further improving the quality of industrial development and promoting service industries (especially finance), and becoming an important driver for the promotion of urban innovation development;

(3) Compared with factor inputs and the development environment, the external linkage differences brought about by location and the gradual opening-up policy have significantly different influences on different types of cities. The enhancement of transportation accessibility has both positive and negative effects on urban innovation development, by influencing the distribution of innovation factors. Specifically, with the coordinated development of innovation and the cross-regional transfer of industries, the deepening of integration provides conditions for under-developed cities in peripheral areas to participate in industrial transfer, and take advantage of innovation spillover from developed cities. For high–high cities, the change in comparative advantage brought by economic development, especially the increase in the costs of labor and land, is also accompanied by the spillover of some labor-intensive industries. For example, the coordinated construction of the G60 corridor, and the accelerated transfer of labor-intensive industries from Zhejiang to Anhui in recent years, are among the important factors for the significant negative effect. Participation in global competition also has a complex effect on the urban innovation [4]. For low–low cities, the low-quality of foreign investment, and the significant gaps in urban innovation levels, are important reasons for the significant negative effect. For low–high and high–high cities, the narrowing of the technological gap with foreign countries brought by the enhancement of urban innovation, the decrease in innovation effect relanced on external channels, the competition for high-end innovation resources, and the innovation "crowding-out effect" of foreign capital [8,27], as well as the transnational industrial transfer in high-level opening-up, all have impacts on urban innovation development; the non-significant negative effect suggests that independent innovation should become an important guide for urban innovation development in the future.

5.3. Better Formulation of Policies to Support Integrated Innovation Development

Innovation is a key driver of high-quality urban development. However, in the context of China's macro-strategic adjustment and accelerated industrial transfer in recent years, the transformation of regional economic development patterns has not led to a simultaneous evolution of innovation patterns [30], indicating that there is still a long way to go with regard to promoting a rational layout of innovation resources in urban agglomerations and guiding coordinated innovation development. Promoting coordinated urban innovation is an important element in the implementation of China's innovation development strategy. Although the innovation space cannot be evenly distributed [8], the significant innovation gradient among urban agglomerations indicates that innovation chain-based vertical collaboration, and division of labor between cities, should be strengthened, based on the foundation of urban development, for example, promoting the transfer and transformation of related industries and innovation achievements from developed cities to surrounding areas, and improving innovation efficiency through cooperation, which are important directions for the development of high-quality innovation in urban agglomerations.

From the perspective of the driving factors for innovation development, with improvements in urban development, and changes in internal and external development environments, the driving factors in different periods manifest as the intensification of factor inputs and external linkage effects, as well as the differentiation of the effect of urban development. In the accelerated transformation of the macro strategy of urban agglomeration from "polarized development" to "coordinated development", the development level and business environment of under-developed cities significantly improve. However, under the influence of boundary barriers, location conditions, and policy bias, the distribution of innovation resources in the YRD still exhibit a strong "Matthew effect", leading to the stabilization of "core–periphery" differences in innovation. In the process of collaborative innovation, it is necessary not only to optimize the quality and quantity of the input factors for urban innovation, but also to formulate scientific policies to guide innovation cooperation based on industrial chains, for example, building integrated transportation facilities, lowering barriers to the cross-regional flow of resources, deepening high-level opening-up and coordination, and co-establishing a modern financial support system to promote the coordinated development and competitiveness of urban agglomerations, through a reasonable and orderly environment and support system for innovation factors. However, changes in the driving factors for innovation indicate that relevant policies should be formulated to "keep up with the times".

With the transformation of regional development patterns, the deepening of integration, and the evolution of factor competition, there are certain differences in the effects of relevant driving factors in different regions, indicating that, in the process of guiding urban innovation development in the future, differentiated means should be adopted at different development stages and in different regions to promote higher-quality innovation development in urban agglomerations through "precise policy implementation". For high-level central cities, while further improving the quality of innovation, they should enhance the spillover effect of innovation in internal opening-up, and shift from "attracting investments" to "selecting investments" in external opening-up, in order to cultivate local independent innovation capacity and build a highly competitive innovation-led zone. For other developed cities, they should make full use of their own manufacturing development base, take advantage of their good locations, further strengthen joint innovation efforts with cities such as Shanghai and Hangzhou, build cross-border external channels to promote innovation interactions with other cities, concentrate high-end foreign investment, and strive to achieve new advantages in the transformation of S&T achievements and innovation in key fields. For under-developed cities, based on their own comparative advantages in resources and natural environments, they should accelerate their innovation development and catch-up strategies, optimize their own development environment, construct high-level drivers for internal and external opening-up, and build a reasonable path to regional innovation network integration, so as to enhance the efficiency of innovation with more a precise policy implementation.

5.4. Research Limitations

Limited by data availability, there is still room for further improvement of this research. First, there are three types of patents (i.e., invention, utility model, and appearance design), and there are significant differences in the technical level and economic and social benefits of different patents. However, the present study does not differentiate between the three types of patents for in-depth comparisons. As a complex "input–output" system, urban innovation development is the result of the combined effect of multiple factors, including measurable factor inputs, as well as non-measurable policies and spatial linkages. Although this research constructs an econometric model based on the KPF, the selection and measurement of the driving factors need to be optimized. As an example, the differentiated innovation support policies in different cities, and the level of cross-city innovation linkages, are not adequately considered. These equally important issues require in-depth consideration and study in the future.

6. Conclusions

As the largest developing country in the world, innovation is a core driver of China's high-quality development. In the context of China's accelerated construction of the "19 + 2" urban agglomeration development pattern, and the upgrading of the regional integration development of the YRD as a national strategy, the present research uses the CV, Gini coefficient, and NICH to explore the evolution of innovation spatio–temporal patterns in the YRD from 2000 to 2018, and to carry out a multi-faceted and quantitative investigation of driving factors for innovation development. The main findings are as follows. Since the beginning of the 21st century, the innovation level in the YRD significantly improves, accompanied by the weakening of innovation differences among cities. However, the larger CV and Gini coefficient indicate that the gap in innovation level between cities is still large, which is a key factor limiting balanced development. Therefore, stimulating the innovation development of cities, especially under-developed cities, is one of the important directions to promote coordinated regional development in the future. From the perspective of urban agglomeration comparison, whether the relevant features are universal is worthy of further in-depth study.

Unbalanced development is one of the important features of China's economic growth. Differences in location, resource endowment, and macro policies of different cities brought about significant gaps in innovation levels. The analysis of spatio–temporal pattern evolution reveals that although the innovation level of some peripherical cities improves, the innovation pattern of urban agglomeration shows stable "core–periphery" and "south–north" differences, with a "Z"-shaped belt space with cities such as Shanghai, Nanjing, Hangzhou, and Ningbo as nodes, and always being the active innovation axis of urban agglomeration. The analysis of the pattern of innovation growth based on the NICH finds that fast-growing cities are clustered in the core area, and that the increase in high-growth cities is characterized by proximity diffusion. Both spatial and temporal comparisons show that the innovation development gap in the YRD is large, and this situation is highly stable. In this regard, it is necessary to give full play to the government's macro-control role to narrow the innovation development gap. However, in this process, relevant policies should be formulated to "keep up with the times" and "adapt to local conditions". In the follow-up research, it is of great practical significance to deeply explore the formation mechanism of the development gap steady-state.

Scientific identification of drivers is an important foundation to better promote innovation development and narrow the innovation development gap. Based on the empirical study of knowledge production function, this paper finds that factor inputs, urban development state, and external linkages are all important driving factors for urban innovation development in the YRD. However, with improvements in the urban development level, and the changes in internal and external development environments, the driving factors in different periods manifest as the intensification of factor inputs and external linkage effects, as well as the differentiation of urban development state effects. This shows that in factor-driven innovation development, cities should not only increase the input of innovation factors, but also work on the quality of factors and innovation environment, such as strengthening innovation connection with developed cities in urban agglomerations. Based on the NICH in different periods, the cities are divided into low–low, low–high, high–low, and high–high types, and this is our possible theoretical contribution to the classification method of urban innovative development types. The results of the quantitative study reveal that there are differences in the driving factors for innovation in different types. For example, the innovation in low–low cities is mainly driven by factor inputs, urban development state, and internal opening-up, and innovation in low–high and high–high cities is largely influenced by factor inputs and urban development state. The differences in the evolutionary characteristics and driving factors of innovation development indicate that cities should actively explore innovation paths suitable for their own development, and fully consider their reasonable positioning in the innovation pattern of urban agglomerations. For example, developed cities should enhance the driving effect through industrial transfer, and under-developed cities should optimize the development environment, improve the factor concentration level, and enhance endogenous growth momentum. In general, the efficiency of urban innovation development, and the quality of innovation, can be maximized through the multi-faceted synergy within and among cities. Further directions for investigation, based on more detailed data, such as the effect evaluation of government policies and the comparative research on the driving factors on a finer scale, are of great significance to better promote the innovative development of urban agglomerations.

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Analysis of the Spatial and Temporal Characteristics and Dynamic Effects of Urban-Rural Integration Development in the Yangtze River Delta Region

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Abstract: Urban-rural integration has been found to be an inevitable trend in the development of urban-rural relations and a vital measure to tackle the unbalanced and uncoordinated development between urban and rural areas. Most existing studies on the development of urban-rural integration have only estimated its level and factors and compared the heterogeneity of cities in sample regions. Few studies have focused on the interactions between different categories of urban-rural integration levels. Accordingly, to fill the above research gap, an evaluation index system of the development of urban-rural integration is built in this study from four economic-social-spatial-ecological dimensions, the spatial and temporal evolution characteristics of the development of urban-rural integration in 27 central cities in the Yangtze River Delta region between 2003 and 2020 are analyzed, and the intrinsic dynamic shock effects are empirically investigated using a panel vector autoregression (PVAR) model. This study suggests the following points: (1) the development of urban-rural integration in the Yangtze River Delta region tends to increase while fluctuating and experiences an evolutionary process of "severe dysfunction–moderate dysfunction–mild dysfunction", with an overall positive development trend. (2) In the study period, the agglomeration effect of the level of the development of urban-rural integration in the Yangtze River Delta has been strengthened continuously, and the overall spatial distribution pattern has changed from "low level, low gap" to "high level, high gap", showing the characteristics of decreasing class distribution step by step, with Shanghai and Anqing as the markers from east to west. (3) All the endogenous variables of the development of urban-rural integration show a continuous positive response to their own shocks, thus suggesting that the respective variable has a certain path dependence on itself. Shocks of urban-rural ecological integration are capable of boosting the improvement of urban-rural economic integration and urban-rural social integration development, and shocks of urban-rural social integration contribute to the improvement of urban-rural ecological integration. The important policy implication of this study is that an intra-regional linkage and coordination mechanism should be built in the future, while the focus should be placed on the heterogeneity of regional development, and policies and measures regarding development of urban-rural integration in a disaggregated manner should be developed, so as to facilitate the improvement of the level of regional development of urban-rural integration.

Keywords: Yangtze River Delta region; urban-rural integration; spatio-temporal evolution; dynamic shocks

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1. Background of the Study

In the course of urbanization and modernization, developed and developing nations are facing the decline in the countryside, and the gap between rural and urban areas is becoming increasingly prominent in numerous parts of the world [1]. Thus, the correlation between urban and rural development should be stressed in all periods of economic development, which is the most fundamental economic and social relationship in a country, and as an integral part of the urban and rural territorial system, the two have always been an inseparable organic fusion [2]. With the continuous promotion of urbanization, the interaction between urban and rural areas is becoming increasingly closer, thus promoting the continuous transformation of urban and rural development. However, unlike developed nations, urbanization in developing nations is often at the expense of the development of rural areas, which causes inequality in the flow of a considerable number of factors and the decline in rural areas [3]. Accordingly, the question of how to achieve integrated rural-urban development and rural rejuvenation has become a common challenge for all nations worldwide, and it takes on great significance in achieving the goal of global sustainable development.

China is the world's largest developing country. Its long-standing dualistic system of urban-rural division and urban-oriented view of development has exacerbated the "three divisions" of urban-rural division, land division, and separation of people and land. This system has been found as the root cause of the increasingly serious "rural disease", which has significantly restricted the integration of urban and rural areas and the healthy development of the countryside in China [4]. Scholars have generally suggested that the evolution of urban-rural relations in China has experienced a process of separation, confrontation, coordination, and then integration [5]. Since the beginning of the 21st century, the Chinese government has begun to address the contradictions between urban and rural development and has implemented a series of policies and measures conducive to rural development, successively proposing integrated urban-rural development, coordinated urban-rural development (cheng xiang tong chou), urban-rural unity (cheng xiang yi ti hua), as well as integrated urban-rural development (cheng xiang rong he). To be specific, urban-rural coordinated development emphasizes the means by which the government can enhance the correlation between urban and rural areas by allocating resources. Urban-rural unity aims to weaken the individuality of urban and rural areas, which ignores the uniqueness of rural development itself. Urban-rural integrated development stresses the equality of status between urban and rural areas, in which urban and rural areas achieve joint development via the two-way flow of factors and the effective allocation of resources.

The development of urban-rural integration is now highly valued by the Chinese government, and it has been proposed at several important meetings to develop a novel urban–rural relationship of co-prosperity and interaction by establishing institutional mechanisms for the development of urban-rural integration. Moreover, the strategy of rural revitalization has been proposed to emphasize the intrinsic motivation of rural development through the priority allocation of rural resources, so as to achieve prosperity and wealth in rural areas. It has been generally considered that from the urban-rural development of nations worldwide, integrated urban-rural development is critical to solve the imbalance between urban and rural development, and it is also the inevitable trend of the urban–rural development relationship in the new era. Promoting integrated urban-rural development has been found to be inevitable to boost the development of China's rural revitalization in the new era, an inevitable demand for China's high-quality economic development in the new era [5], as well as a major strategy to achieve China's modernization and sustainable development. Accordingly, as China's macro-strategic policies are being implemented, the study of promoting integrated urban-rural development takes on critical significance in reshaping the correlation between urban and rural development, exploring the laws of urban-rural development evolution and investigating the path of urban-rural integrated development. Furthermore, the measurement and analysis of the state of regional development of urban-rural integration lay a basis for the transformation from qualitative to quantitative development of urban-rural integration, which is of high significance in narrowing the regional development gap and promoting coordinated regional development.

The urban–rural relationship is a vital issue in human social development and has aroused wide attention from scholars worldwide. Urban-rural integration is an advanced stage in the development of urban-rural relations and reflects the evolution of urban-rural relations, which can be traced back to the urban-rural development concept of the ideal socialists [6]. Existing research on the development of urban-rural integration primarily focuses on the theory of urban-rural relations, connotation elaboration and level measurement, and attempts to measure the level of regional development of urban-rural integration and explore its intrinsic factors by constructing a comprehensive index system [7–14]. However, first, only a small proportion of the existing research has investigated the inner mechanism of the development of urban-rural integration. Second, Most of the studies have built the evaluation index system from a static perspective, which cannot indicate the dynamic and comprehensive nature of the development of urban-rural integration in a scientific and comprehensive manner. Third, studies on the development of urban-rural integration have been largely at the national or provincial level, and there is a lack of spatial and temporal studies at the city scale.

The Yangtze River Delta region, the critical economic growth pole in China, shows a significant strategic position in China's all-round construction and opening-up pattern, and the integration of the Yangtze River Delta is a vital engine of China's economic development [15]. Regional economic development has been highly valued by the Chinese government. The Yangtze River Delta is a region with Shanghai, which comprises nine prefecture-level cities in the Jiangsu Province, nine prefecture-level cities in the Zhejiang Province, and eight prefecture-level cities in the Anhui Province as the central cities. This region has been driving the integrated development of the whole region by radiation. Under the development of the new era, urban-rural integration serves as an essential means to tackle the contradictions between urban and rural development in the Yangtze River Delta region. Moreover, urban-rural integration takes on great significance in boosting the high-quality economic and integrated regional development of the region. In the context of coordinated regional economic development, this raises the questions of what is the trend of urban-rural integration development in the Yangtze River Delta region, what are the spatial characteristics and effects of regional urban-rural integration, as well as what dynamic effects exist between regional urban-rural integration development systems. Accordingly, 27 central cities in the Yangtze River Delta region are selected as the research objects to develop a multi-dimensional urban-rural integration evaluation index system to measure the level of the development of urban-rural integration, and its spatial and temporal evolution characteristics are analyzed. Subsequently, a panel vector autoregression (PVAR) model is built to measure the dynamic impact effects between different dimensions of the development of urban-rural integration. Next, an empirical study is conducted to examine the dynamic impact effects between the dimensions of the development of urban-rural integration by building a panel vector autoregression (PVAR) model, so as to explore the interactive effects between the intrinsic dimensions and to provide scientific reference and suggestions for facilitating the development of urban-rural integration in the Yangtze River Delta region.

2. Definition and Mechanistic Description

2.1. Definition of Connotation

With the continuous promotion of urban-rural integration strategies, the factors between urban and rural areas have changed rapidly, thus gradually breaking down the boundaries, structures and even mechanisms of action between urban and rural areas [16], and the long-existing "dualistic order" has triggered the endogenous demand for "common (integrated) development". Driven by urbanization and industrialization, urban-rural territorial systems tend to be more coordinated, and their functions and structures are becoming multi-dimensional. Scholars in ecology have concluded that urban-rural integration should achieve the elimination of the imbalance of ecological development between urban and rural areas, while scholars in geography have suggested that urban-rural integration should be a rational spatial connection between urban and rural systems. Other scholars have clarified the connotation of urban-rural integration in accordance with "flow space" and urban-rural equivalence theory and have argued that in the era of rapid development of information technology, conventional factors (e.g., land and population) break through the limitations of the field and exhibit dynamic and networked characteristics, thus affecting the mechanism of urban-rural factor flow [17,18]. In addition, the connotation of the development of urban-rural integration in accordance with the theory of urban-rural equivalence highlights the "different but equal" nature of urban-rural development. In brief, the integrated development of urban and rural areas should be achieved through the two-way flow of factors and the effective allocation of resources to achieve the interaction and integration of the economic, social and ecological fields of the urban and rural regional systems, and ultimately the development of urban and rural equivalence. The above process also refers to the transformation of the heterogeneous dual structure into a homogeneous monolithic structure, which is essential to the development of urban-rural integration [6].

As revealed by the above theoretical analysis, integrated urban-rural development is a complex, multi-level and multi-element composite structural system with profound connotations. The core meaning of urban-rural integrated development lies in the premise of ensuring the effective allocation of urban and rural factors and resources in both directions, realizing the co-prosperity and co-existence of urban and rural areas through the benign interaction between urban and rural areas, realizing the multi-dimensional integrated development of urban and rural areas in economic, social, ecological and spatial aspects, and ultimately realizing the equivalence of urban and rural regional systems [9]. The specific connotation is presented below. Urban-rural economic integration means that the marginal rewards of urban and rural areas tend to be equal through the two-way flow and optimal allocation of resources and factors under equal economic policies; urban-rural social integration means ensuring that public services (for example., employment, education, medical care and infrastructure) are of equal significance in urban and rural residents; urban-rural ecological integration is achieved through comprehensive and collaborative management of urban and rural regional systems to achieve a state of high integration and complementarity of urban and rural areas. Urban-rural spatial integration refers to the interaction and integration of urban and rural systems in terms of human, logistic and information flows, which is the carrier and basic condition for urban-rural integrated development (Figure 1).

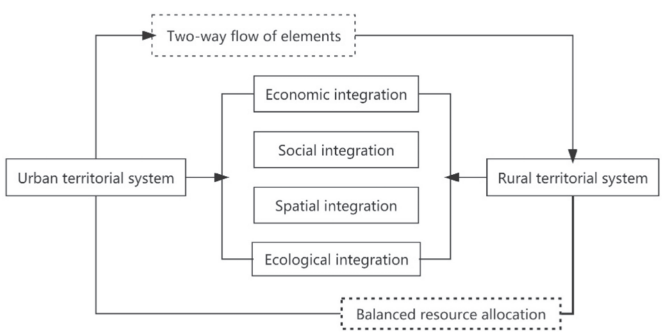

Figure 1. Conceptual framework for integrated urban-rural development.

2.2. Mechanistic Elaboration

Under the goal of regional development, integrated urban-rural development should also achieve a unified process of achieving economic-social-ecological benefits of the urban-rural territorial system and a process of spatially balanced development of the urban-rural territorial system [19]. Accordingly, the theory of regional spatial equilibrium model can be borrowed to construct a spatial equilibrium model of urban-rural integrated development to reveal the inner mechanism of urban-rural integrated development [20].

Thus, we first assume that under integrated regional urban-rural development, various factors of production (including population) in the region are free to move. The comprehensive development benefits of regional development (ΣF_M) consists of social benefit F_1, economic benefit F_2 and ecological benefit F_3; and if it is assumed that a certain type of development benefit A_M is composed of land B_M, labor C_M, technology D_M, and capital E_M and other factors of production, then the expression of the function is as follows:

$$\Sigma F_M = F_1 + F_2 + F_3 \tag{1}$$

$$A_M = f(B_M,\ C_M,\ D_M,\ E_M)\ (M = 1, 2, 3) \tag{2}$$

Under integrated urban-rural development, through the flow and optimal allocation of factors, urban and rural territorial systems can eventually achieve equal development benefits per capita in urban and rural territorial systems, i.e., eventually realize the equivalence of urban and rural development, and the expression of the model of balanced urban-rural development [21].

$$OF_1 = \frac{\Sigma D_{1M}}{O_1} = \frac{\Sigma D_{2M}}{O_2} = OF_2 \tag{3}$$

In this equation, ΣD_{1M} and ΣD_{2M} denote the combined development benefits of rural and urban areas, respectively. O_1 and O_2 represent the total rural and urban populations, respectively. OF_1 and OF_2 express the combined development benefits per capita in rural and urban areas, respectively. Equation (3) is derived based on the assumption that the goods (services) generating social development benefits in rural and urban areas are private goods, whereas social and environmental development benefits are mostly public or quasi-public goods in reality, thus making it difficult to avoid the existence of non-exclusive, non-competitive and indivisible characteristics. Accordingly, to obtain per capita development benefits in the above cases, the spatial equilibrium model should be modified using a correction factor.

$$OF_1 = \frac{\Sigma D_{1M}}{\alpha_1 O_1} = \frac{\Sigma D_{2M}}{\alpha_2 O_2} = OF_2\left(\alpha_1 \in \left(\frac{1}{O_1}, 1\right), \alpha_2 \in \left(\frac{1}{O_2}, 1\right)\right) \tag{4}$$

This model is an extension of the idea of balanced regional development theory and can more effectively explain the inner mechanism of integrated urban-rural development [22]. In line with the above connotation explanation, the two-way flow of factors between urban and rural areas and the optimal allocation of resources are vital prerequisites for achieving integrated urban-rural development. First, relevant studies have found that China's urbanization level is still lower than the average of comparable nations in the world [23]. Second, as the level of integrated development between urban and rural areas is being improved, increasing modernization factors in cities are allocated to rural systems, which are manifested as the net inflow of capital, technology and other factors. Third, with the implementation of the rural revitalization strategy, the proportion of basic public services in rural areas is increasing, which is manifested as an increasing proportion of public goods. Through the flow and optimal allocation of factors between urban and rural areas, the population of rural areas (O_1) tends to decrease within a certain range, along with the continuous promotion of urbanization. Through the input of various factors from cities and the implementation of the rural revitalization strategy, the comprehensive development efficiency of the rural territorial system tends to increase, which means that the per capita development efficiency of the rural territorial system is increasing, and the spatial, economic and social distribution of the urban and rural territorial system is optimized. As a result, the per capita development efficiency of the urban and rural territorial system eventually tends to be equalized, and the integrated development of urban and rural areas is achieved.

3. Selection of Indicators and Research Methodology

3.1. Selection of Indicators

As mentioned earlier, the key to the development of urban-rural integration lies in the process of transformation from a heterogeneous dual structure to a homogeneous monolithic structure, and the development of urban-rural development from dichotomy to full integration is bound to undergo a dynamic process of evolution from spatial imbalance to urban-rural equilibrium. From this perspective, urban-rural integration is a goal and a state, as well as a process. Thus, the selection of indicators of the development of urban-rural integration should break through the previous static scope, and include indicators of urban-rural comparison and difference (comparison category), as well as indicators reflecting "urban-rural interaction and integration" (driving category), and also indicators of urban-rural development status (comprehensive category). In brief, according to the connotation and mechanism analysis of the development of urban-rural integration, and using the frequency analysis method and the expert validation method to determine the indicators one by one, twenty indicators in four dimensions, including economic, social, ecological and spatial dimensions, are finally determined (Table 1), and twenty-seven central cities in the Yangtze River Delta region are selected for the study, including Shanghai, Nanjing, Suzhou, Wuxi, Changzhou, Yancheng, Taizhou, Yangzhou, and Yangzhou in Jiangsu Province, Yancheng, Taizhou, Yangzhou, Zhenjiang, and Nantong in Jiangsu Province, Hangzhou, Wenzhou, Ningbo, Huzhou, Jinhua, Jiaxing, Shaoxing, Tai'zhou, and Zhoushan in Zhejiang Province, as well as Hefei, Maanshan, Wuhu, Tongling, Chuzhou, Anqing, Chizhou, and Xuancheng in the Anhui Province. The world has witnessed a rapid urbanization trend over the past few years. Moreover, numerous urban agglomerations have emerged. Similar to the Yangtze River Delta urban agglomeration, the Northeast Atlantic coastal urban agglomeration and the five major urban agglomerations in North America have been formed in foreign countries [24]. The above urban agglomerations are characterized by superior location conditions, higher levels of comprehensive economic development, developed transportation, advanced industrial structure, as well as closer interactions between urban and rural areas. Accordingly, the urban-rural integration index system constructed in this study can also explain the development trend of urban-rural integration in the development of urban agglomerations in other regions. In addition, urbanization is an inevitable result of socio-economic development and a manifestation of social progress. The urban-rural integration development indicators established in this study can also lay a theoretical basis for urban-rural integration in developing countries and provide a reference for cities in developed countries to feed their villages.

Table 1. Urban-rural integration evaluation indicator system.

Objectives	Subsystems	Indicator Layer	Description or Calculation of the Indicator	Properties	Type of Indicator
Level of urban-rural integration	Economic integration	GDP per capita	Total regional GDP/total regional population/yuan	Positive	General
		Non-farm industry ratio	Primary industry output/secondary and tertiary industry output/%	Negative	Contrast category
		Ratio of urban to rural Engel's coefficient	Urban Engel's coefficient/rural Engel's coefficient/%	Negative	Contrast category
		Ratio of urban to rural household consumption per capita	Rural per capita consumption/urban per capita consumption/%	Negative	Contrast category

Table 1. *Cont.*

Objectives	Subsystems	Indicator Layer	Description or Calculation of the Indicator	Properties	Type of Indicator
		Ratio of urban to rural per capita income	Urban per capita income/rural per capita income/%	Negative	Contrast category
		Fixed asset investment per capita in urban and rural areas	Urban and rural fixed asset expenditure/total population/yuan/person	Positive	Drivers
	Social integration	Ratio of urban to rural expenditure on culture, education and recreation	Urban residents' expenditure on culture, education and recreation/rural residents' expenditure on culture, education and recreation/%	Negative	Contrast category
		Ratio of health care expenditure per capita in urban and rural areas	Urban per capita health expenditure/rural per capita health expenditure/%	Negative	Contrast category
		Comparative coefficient of urban and rural transport communications	Urban per capita expenditure on transport and communication/rural per capita expenditure on transport and communication/%	Negative	Contrast category
		Urban and rural pension insurance coverage	%	Positive	General
		Urban and rural unemployment insurance coverage	%	Positive	General
		Percentage of practicing physicians in urban and rural areas	Number of practicing doctors in urban and rural areas/total population/%	Positive	General
	Ecological integration	Urban and rural domestic waste treatment	%	Positive	General
		Sewage treatment factor	Urban and rural sewage treatment rate/%	Positive	General
		Industrial solid waste disposal	Urban and rural industrial solid waste disposal rate %	Positive	General
	Spatial integration	Level of land urbanization	Area of built-up area/total land area/%	Positive	Drivers
		Level of population urbanization	Urban population/total population (%)	Positive	Drivers
		Urban and rural mobility network	Road mileage in operation/total land area (km/km^2)	Positive	Drivers
		Urban spatial expansion factor	Area of built-up area/area under crop cultivation/%	Negative	General
		Urban and rural employment headcount coefficient	Ratio of urban to rural population employed/%	Negative	General

3.2. Research Methodology

- Measuring the level of the development of urban-rural integration

Since the subjective assignment method cannot overcome the problem of credibility reduction caused by human subjectivity, the coefficient of variation method is adopted in this study to determine the weights of the respective indicator. The coefficient of variation method is an objective auxiliary method that measures the degree of differentiation of data by calculating the ratio of the standard deviation to the mean of the data, so as to calculate the weights of indicators. The advantage of this method is that it eliminates the degree of dispersion in unit means and the effect of different units or means on the comparison of the degree of variation brought about by multiple samples [25]. The raw data are normalized using the most common extreme value normalization method. The specific equation for the coefficient of variation method is written as follows:

$$\rho_{ij} = \frac{\sigma_{ij}/\overline{x}_{ij}}{\sum_{i=1}^{j}(\sigma_{ij}/\overline{x}_{ij})} \tag{5}$$

In this equation, σ_{ij} denotes the standard deviation of the jth indicator of the ith dimension; $\overline{X}_{ij}$ denotes the mean value of the jth indicator of the *i*-th dimension; ρ_{ij} represents the weight of the jth indicator of the i-th dimension. After the weight of the respective indicator is obtained using Equation (5), the Euclidean distance method in Equation (6) is adopted to obtain the evaluation value of urban-rural integration in the central cities of the Yangtze River Delta between 2003 and 2020, and the values of the economic, social, ecological and spatial dimensions are calculated.

$$Y_i = 1 - \frac{\sqrt{(\rho_{i1} - \rho_{i1}X_{i1})^2 + (\rho_{i2} - \rho_{i2}X_{i2})^2 + \cdots + (\rho_{ij} - \rho_{ij}X_{ij})^2}}{\sqrt{\rho_{i1}^2 + \rho_{i2}^2 + \cdots + \rho_{ij}^2}} \tag{6}$$

- Exploratory spatial analysis

The first law of geography indicates that things are interconnected and the closer they are, the more interconnected they will be [25]. Based on the two-way flow of urban and rural factors, urban and rural areas are becoming more closely connected, so the Moran's *I* index should be applied to the ESDA method to measure the spatial dispersion pattern of the central cities in the Yangtze River Delta. Moran's *I* index, used for the spatial agglomeration or spatial distribution characteristics of the whole sample and local area, respectively, is written as the following:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}(x_i - \overline{x})(x_j - \overline{x})}{s^2\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}} \tag{7}$$

$$I_i = \frac{(x_i - \overline{x})\sum_{j=1}^{n}\omega_{ij}(x_i - \overline{x})(x_j - \overline{y})}{s^2} \tag{8}$$

In these equations, x_i and x_j denote the regions; *i* and *j* represent the spatial sequences of region *i* and region *j*, respectively; $\overline{x}$ expresses the mean of the observed values; *n* is the number of cities in the total sample; s^2 is the variance of the sample; ω_{ij} is the spatial matrix. If the region *i* and *j* are adjacent to each other, ω_{ij} = 1 and vice versa. The Moran's I index takes the value $[-1, 1]$ with an I index over 0, indicating a positive correlation effect between regions, i.e., high value-high value adjacency, low value-low value adjacency and vice versa, or indicating a negative effect, high value-low value agglomeration or low value-high value agglomeration.

- PVAR model construction

Hermann Haken's synergetic theory suggests that there are elements (two and more) in a system that interact with and affect each other over time, and the coordination between elements determines the structural tendencies of the system's development [26,27]. The PVAR models are adopted to analyze the dynamic shocks of stochastic perturbations to a system of variables through impulse response functions to explain the effects of various dynamic shocks on the formation of system variables [23]. It can be used to explain the dynamic shock effects between the different system dimensions of urban-rural integration. The PVAR model built in this study is as follows:

$$Z_{it} = \Upsilon_0 + \sum_{j=1}^{m} \Upsilon_j Z_{it-j} + \lambda_i + \xi_{it} + \zeta_{it} \tag{9}$$

where i represents the central city (i = 1, 2, ..., 27), the t represents the year (t = 0, 1, ..., 18), and j Zit = (LNP_{it}, LNH_{it}, LNL_{it}, LNE_{it}), denotes the number of lag periods (j = 1, 2, ..., m) for the first i 4 × 1 dimensional endogenous variables of the city in year t, i.e., urban-rural economic integration variables, urban-rural social integration variables, urban-rural ecological and environmental integration variables, as well as urban-rural spatial integration variables; Z_{it-j} denotes the Z_{it} lagged j period of the variables; γ_0 denotes the vector of intercept terms; γ_j denotes the lag period coefficient matrix, λ_i denotes a vector of fixed effects among the 10 cities, indicating the heterogeneity of the individual cities. ξ_{it} denotes a vector of time effects, suggesting year-specific shock effects in each year. ζ_{it} denotes a vector of random disturbance errors.

- Data sources

The data required for this study are largely obtained from the statistical yearbooks of the central cities of the Yangtze River Delta from 2004 to 2021, the China City Statistical Yearbook, government websites of the cities, websites of statistical bureaus and statistical bulletins. The missing data for some years are filled in by interpolation of adjacent years or linear interpolation.

4. Analysis of Results

4.1. Chronological Evolutionary Characteristics of Integrated Urban-Rural Development

Figures 2 and 3 show a graph of the changes in the level of the development of urban-rural integration in the Yangtze River Delta region and the changes in the level of urban-rural integration in the respective central city, which is analyzed as follows.

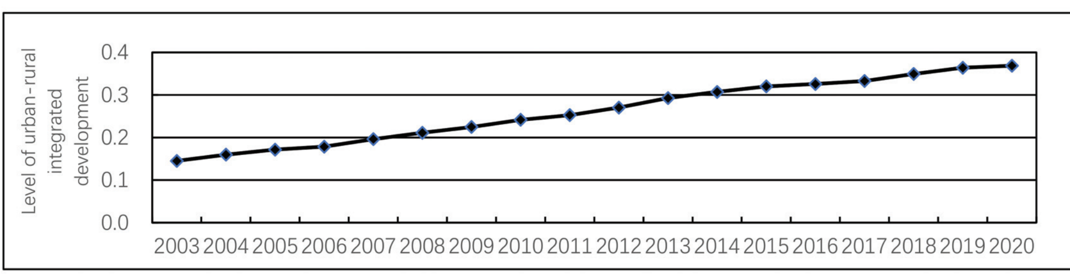

Figure 2. Changes in the level of urban-rural integration development.

As depicted in Figure 2, the level of the development of urban-rural integration in the Yangtze River Delta region has been fluctuating while increasing between 2003 and 2020. It has increased from 0.145 in 2003 to 0.369 in 2020, marking an increase of 154%, with an average annual increase of 8.56%, of which the level of the development of urban-rural integration from 2019 to 2020 has increased the least by only 1.3%, due to the effect of the COVID-19 pandemic. Overall, the evolution of the development of urban-rural integration in the Yangtze River Delta region has been largely consistent with the adjustment of China's macro policies, from the "integrated development of urban and rural areas" released by the 16th Party Congress (2003–2012) to the "integrated development of urban and rural areas" of the 18th Party Congress (2012–2017) to the "integrated development of urban and rural areas" issued by the 18th Party Congress (2012–2017), and then to the 19th Party Congress "integrated urban-rural development" (2017-present), coupled with the deployment of strategies (e.g., the construction of beautiful countryside and the rural revitalization strategy); the level of integrated urban-rural development in the Yangtze River Delta region has been continuously improved.

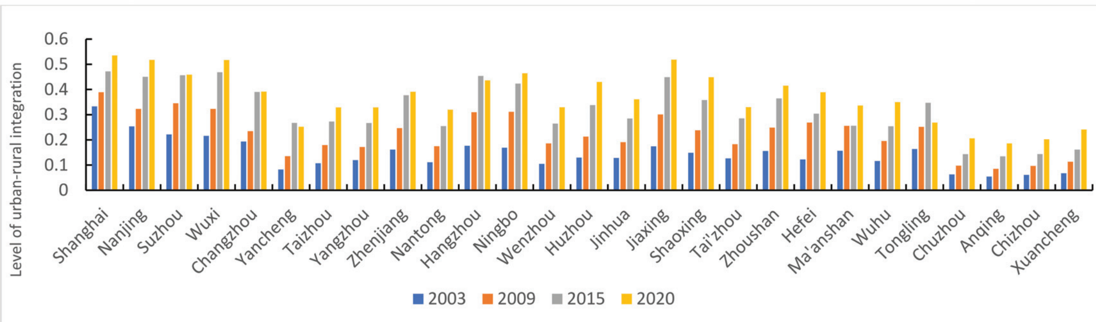

Figure 3. Changes in the level of urban-rural integration development in the central cities of the Yangtze River Delta.

The overall level of the development of urban-rural integration in the central cities of the Yangtze River Delta is low. In the study period, the average level of the development of urban-rural integration in the Yangtze River Delta basically remained around 0.262, and with reference to the classification criteria of related studies [28], the average level of the development of urban-rural integration in the Yangtze River Delta was only at the moderate disorder level, and the level of the development of urban-rural integration in the Yangtze River Delta experienced the evolution process from severe disorder–moderate disorder–light disorder during the period between 2003 and 2020. In 2003, only three cities, Nanjing, Wuxi and Suzhou, were in moderate disorder and Shanghai was in mild disorder, while the rest of the cities were in severe disorder, with the proportion of severe disorder reaching 85.2%. In 2009, the number of cities in severe disorder dropped to 12, accounting for 44.4%, while the number of cities in moderate disorder rose to 8, and 7 cities in mild disorder appeared. By 2020, cities on the verge of dislocation and barely dislocated cities become the main types, with 16 cities; the only central city in heavy dislocation was Anqing, with a reduced proportion of 3.7%; at this time, the level of the development of urban-rural integration in the Yangtze River Delta had raised to a light level. From the above analysis, we can observe that the trend of the development of urban-rural integration in the Yangtze River Delta tends to be positive, showing an essential change from quantitative change to qualitative change, which is fundamentally attributed to the implementation of a series of policies, such as the construction of beautiful countryside and rural revitalization strategy of the Chinese government.

4.2. Analysis of the Spatial Characteristics of Integrated Urban-Rural Development

Using 2003, 2009, 2015 and 2020 as representative years, the spatial and temporal evolutionary characteristics of the development of urban-rural integration in the central cities of the Yangtze River Delta region are analyzed, as shown in Figures 4 and 5.

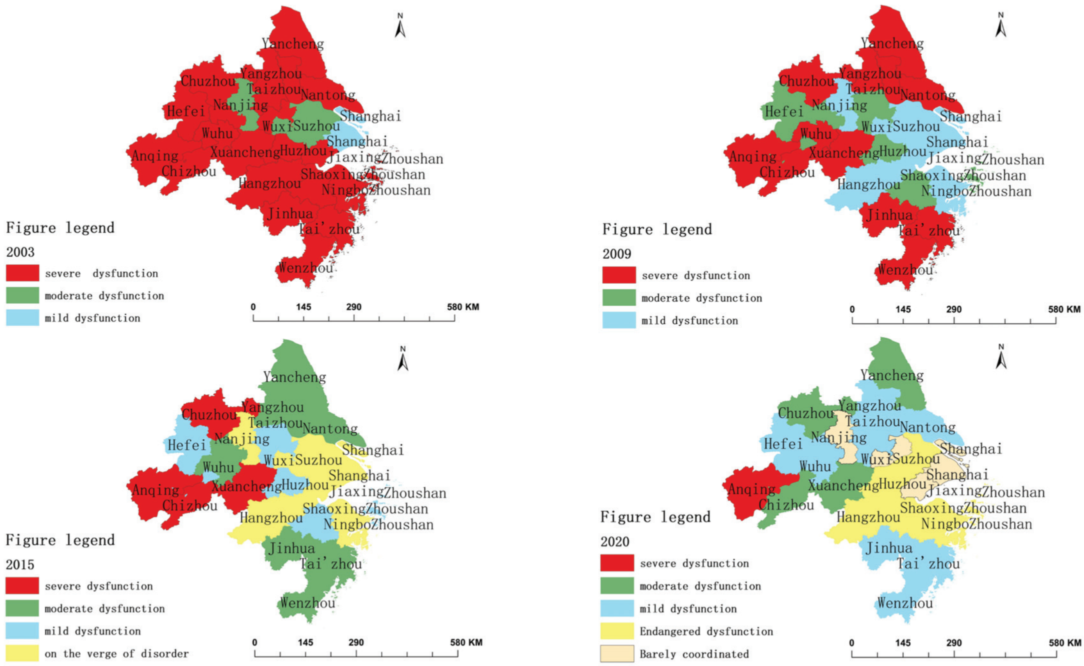

Figure 4. Spatial distribution of urban-rural integration development in the central cities of the Yangtze River Delta (2003–2020).

As depicted in Figure 4, the agglomeration effect of urban-rural integration level in the Yangtze River Delta region is obvious. The high value of the development of urban-rural integration level is primarily concentrated in the central-eastern region and coastal region centered on Shanghai, Suzhou, Wuxi and Jiaxing, thus revealing that the strong economic development strength of Shanghai and Suzhou supports the benign development of their urban-rural integration level, while the low value of urban-rural integration level is largely concentrated in the western and southwestern regions. The spatial distribution pattern shows a change from "low level and low gap" to "high level and high gap".

Figure 5 indicates that there is spatial correlation between the level of urban-rural integration in the Yangtze River Delta region. The Moran's I index for the level of urban-rural integration in the Yangtze River Delta region during the period 2003–2020 is always positive, and the indices are 0.138, 0.145, 0.258 and 0.320 in 2003, 2009, 2015 and 2020, respectively, with the Moran's index showing a gradually increasing trend, thus suggesting that the agglomeration effect of urban-rural integration in the Yangtze River Delta region is gradually increasing, but the gap between regional development of urban-rural integration shows a widening trend, which further highlights the urgency and importance of the Yangtze River Delta integration strategy [27].

The spatial agglomeration effect of the development of urban-rural integration in the Yangtze River Delta region is gradually increasing. As depicted in Figure 5, the local spatial agglomeration effect of the development of urban-rural integration is more significant and is dominated by the HH area (high-high agglomeration type, first quadrant) and the LL area (low-low agglomeration type, third quadrant), and the number of both HH and LL types shows an increasing trend. In terms of the distribution of prefecture-level cities in the quadrants of the Moran index, the main formation is a high value area (H-H) formed by cities such as Shanghai-Suzhou-Wuxi and a low value area (L-L) formed by cities such as Chizhou, Anqing and Tongling. From east to west, roughly with Shanghai and Anqing as the markers, it shows a decreasing hierarchical distribution characteristic. This suggests that the Yangtze River Delta region has a significant spatial neighborhood effect, resulting in a spatial agglomeration distribution characterized by "the weak being constantly weak and the strong being constantly strong".

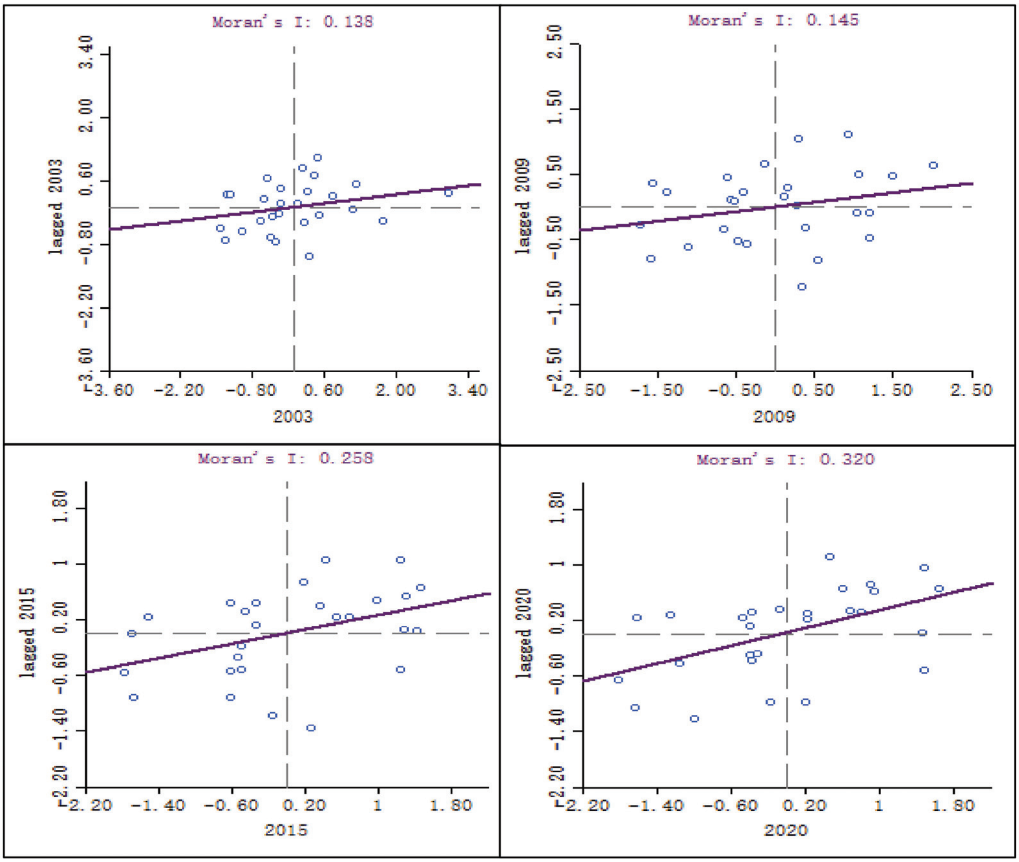

Figure 5. Moran scatterplot of urban-rural integration levels in the Yangtze River Delta 2003, 2009, 2015, 2020.

4.3. Analysis of the Dynamic Impact Effects of the Development of Urban-Rural Integration

4.3.1. Panel Data Testing

First, the PVAR model in Equation (9) is built to explore the dynamic impact effects between the development of urban-rural integration systems in the Yangtze River Delta region, using the evaluation model above to calculate the evaluation values of the development of urban-rural integration sub-dimensions (economic, social, ecological and spatial dimensions) of the respective central city in the Yangtze River Delta region during the period 2003–2020.

To avoid the phenomenon of "pseudo-regression" in the PVAR model, a unit root test of the panel data should be conducted first to ensure the valid estimation of the model [29]. To avoid pseudo-regressions in the PVAR model, a unit root test of the panel data is first conducted to ensure the validity of the model estimates. As shown in Table 2, the first-order differences of the variables all reject the hypothesis that the variables are non-stationary, so Dlnecn, Dlnsoc, Dlneco and Dlnspa can be considered as stationary series, and the PVAR model can be estimated.

Table 2. Unit root test results.

Variables	LLC	IPS
Dlnecn	−4.2623 ***	−3.7429 ***
Dlnsoc	−1.38548 *	−6.0244 ***
Dlnxspa	−10.5302 ***	−7.6842 ***
Dlneco	−5.09022 ***	−7.5705 ***

Note: ***, * indicate significant at 1%, 10% level.

- Determination of the lag order

This study determines the optimal lag order for this study based on the consistent moment model selection criteria proposed by Andrews and Lu (2001). Table 3 shows that MBIC, MAIC and MQIC all have the smallest coefficients at first order, so this study determines the final optimal lag order to be period 1.

Table 3. Optimal lag order of PVAR model.

Lag	CD	*J*	*p*-Value	MBIC	MAIC	MQIC
1	0.999991	50.92931	0.359099	−226.546	−45.0707	−117.506
2	0.999991	31.27899	0.502873	−153.705	−32.721	−81.0111
3	0.999983	14.22208	0.582174	−78.2698	−17.7779	−41.923

- Analysis of GMM estimation results

Dlnecn (economic), Dlnsoc (social), Dlnspa (spatial) and Dlneco (ecological) are employed as the endogenous variables to build a PVAR model for generalized matrix estimation, and the results are listed in Table 4.

Table 4. GMM estimation results.

Dlnecn Z-Value		Dlnsoc Z-Value		Dlnspa Z-Value		Dlneco Z-Value	
L. Dlnecn	5.46 ***	L.dlnx1	1.17	L.dlnx1	0.25	L.dlnx1	−0.88
L. Dlnsoc	0.73	L.dlnx2	1.93 *	L.dlnx2	0.02	L.dlnx2	1.38
L. Dlnspa	0.28	L.dlnx3	−0.86	L.dlnx3	2.21 ***	L.dlnx3	0.72
L.Dlneco	2.9 ***	L.dlnx4	1.83 *	L.dlnx4	−0.8	L.dlnx4	10.23 ***

Note: L. Dlnecn denotes lag 1, ***, * denotes significant at 1%, 10% confidence level, respectively.

For the endogenous variables themselves, Dlnecn has a positive effect with a coefficient of 5.46 at the 1% level, thus suggesting that urban-rural economic integration is significantly dependent on its own inertia development. Dlnsoc, Dlnspa, and Dlnspa have a positive effect with the coefficients of 1.93, 2.21, and 10.21, respectively. The coefficients are 1.93, 2.21, and 10.21, respectively, and are significant at the 10% and 1% levels, respectively, thus suggesting that urban-rural social integration, urban-rural spatial integration and urban-rural ecological integration all have a "sticky" effect on their own development, with the "stickiness" of urban-rural ecological integration being the most prominent. For the correlation between the endogenous variables, Dlnspa positively affects Dlnsoc at the 1% significant level, thus suggesting that urban-rural ecological integration has a positive promotion effect on urban-rural economic integration with a lag of one period, which proves the importance of the theory of "green water and green mountains are the silver mountain of gold". The positive effect of Dlnspa on Dlnsoc at the 10% significant level indicates that there is a positive effect of urban-rural ecological integration on urban-rural social integration at the 1-lagged period; urban-rural economic integration, urban-rural social integration and urban-rural spatial integration on urban-rural ecological integration at the 1-lagged period are not significant, thus indicating that the current socio-economic development of the Yangtze River Delta region has failed to achieve the coordinated development of ecological environment. The impact of urban-rural economic integration, urban-rural social integration and urban-rural ecological integration on the development of urban-rural spatial integration is not significant, thus revealing that the regional economic, social and ecological development has not formed an effective linkage and coordinated development and cannot effectively contribute to the development of urban-rural spatial integration.

- Panel Granger causality test

In this study, the Granger causality test is performed to test whether there is a logical relationship between the variables that affect each other based on GMM estimation, and the results are described in Table 5.

Table 5. Panel Granger causality test.

Original Assumptions	Chi^2 Statistic	*p*-Value
Dlnsco cannot Granger cause Dlnecn	0.54	0.463
Dlnspa cannot Granger cause Dlnecn	0.08	0.777
Dlneco cannot Granger cause Dlnecn	8.394	0.0004
Dlnsco, Dlnspa and Dlneco cannot simultaneously Granger cause Dlnecn	11.929	0.008
Dlnecn cannot Granger cause Dlnsco	1.38	0.24
Dlnspa cannot Granger cause Dlnsco	0.732	0.392
Dlneco cannot Granger cause Dlnsco	3.348	0.067
Dlnecn, Dlnspa, Dlneco cannot Granger cause Dlnsco	8.196	0.042
Dlnecn cannot Granger cause Dlnspa	0.062	0.803
Dlnsco cannot Granger cause Dlnspa	0	0.986
Dlnsco cannot Granger cause Dlnspa	0.643	0.423
Dlnecn, Dlnsco and Dlnsco cannot Granger cause Dlnspa	3.333	0.343
Dlnecn cannot Granger cause Dlnsco	0.767	0.381
Dlneco cannot Granger cause Dlneco	1.915	0.166
Dlnspa cannot Granger cause Dlneco	0.525	0.469
Dlnecn, Dlnsco and Dlnspa cannot Granger cause Dlneco	8.381	0.039

The Dlnecn equation suggests that urban-rural ecological integration is the Granger cause of urban-rural economic integration at the 1% significant level, while urban-rural social integration and urban-rural spatial integration are not the Granger cause of urban-rural economic integration, whereas the joint development of urban-rural social integration, urban-rural spatial integration and urban-rural ecological integration is the Granger cause of urban-rural economic integration at the 1% significant level, thus revealing that the improvement of ecological environment and environmental quality contributes to the economic development, and a certain degree of interaction has been formed between urban-rural ecological integration and urban-rural economic integration. At the same time, this is in line with the connotation of high-quality economic development advocated by the current Chinese government, while the improvement of the level of economic development is also dependent on the coordinated development of social systems, spatial systems, and ecosystems. The Dlnsco equation shows that urban-rural ecological integration is a Granger cause of urban-rural social integration at the 10% significant level, thus suggesting that the improvement of ecological environment quality has a role in the stable development of social systems. Meanwhile, the joint development of urban-rural economic integration, urban-rural spatial integration and urban-rural ecological integration at the 5% significant level is the Granger cause of urban-rural social integration, thus suggesting that the healthy development of urban-rural social system also depends on the coordination and stability of spatial system and ecosystem with economic development. As revealed by the Dlnspa equation, urban-rural economic integration, urban-rural social integration and urban-rural ecological integration and the joint development of the three are not Granger causes of urban-rural spatial integration, thus suggesting that urban-rural spatial integration depends more on the governance and development of the space. As indicated by the Dlneco equation, urban-rural economic integration, urban-rural social integration and urban-rural spatial integration are not the Granger causes of urban-rural ecological integration, whereas the joint development of the three is the Granger cause of urban-rural ecological integration at the 5% significant level, thus suggesting that the improvement of ecological environment level is not only dependent on the input of regional economy, but also on the coordinated development of economic, social and spatial aspects to achieve the qualitative improvement of the ecological environment level.

- Panel AR root test

The AR root test is a vital condition to test whether the PVAR model is stable or not. It is only when all the AR roots are guaranteed to lie within the unit circle that the PVAR model is stable and the results are convincing. As depicted in Figure 6, the PVAR model built in this study has four unit roots and they all lie within the unit circle, so the PVAR model built in this study can be considered stable.

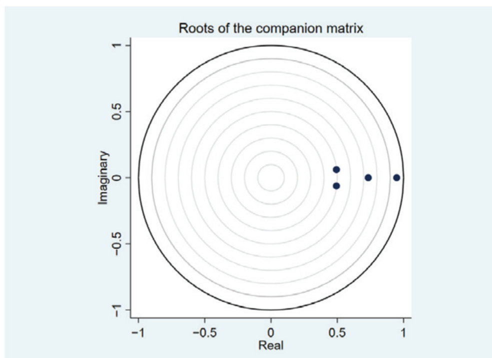

Figure 6. Panel AR root test.

4.3.2. Analysis of Pulse Function Results

The impulse response function refers to a more accurate reflection of the long-term impact relationship between the variables by measuring the short- and long-term effects of the variables on other variables when subjected to shocks with unit differences, with the other variables constant in the current and previous periods [30]. This section will examine the impact of urban-rural economic integration. In this section, one unit standard deviation shocks will be applied to urban-rural economic integration, urban-rural social integration, urban-rural spatial integration and urban-rural spatial integration, respectively, and Monte-Carlo simulations will be set up in stata for 200 times to examine the dynamic shock effects among the variables. Furthermore, since the effects between the variables are not all significant, only the impulse response images with significant results are presented, where the horizontal axis indicates the period of the variable response and the vertical axis is the magnitude of the variable response.

As depicted in Figure 7, the response of all four variables is positive under the shock effect of one standard deviation variable, thus suggesting that urban-rural economic, social, spatial and ecological integration all show a continuous positive response to their own shocks, thus suggesting that the respective variable has a certain path dependence (inertia) on itself; urban-rural ecological integration and urban-rural spatial integration both reach the maximum in the current period and then weaken rapidly, showing a continuous inertia and lag. Both urban-rural economic integration and urban-rural social integration also reach their maximum in the current period and then gradually decrease, whereas this inertia is smaller than that of urban-rural ecological integration and spatial integration.

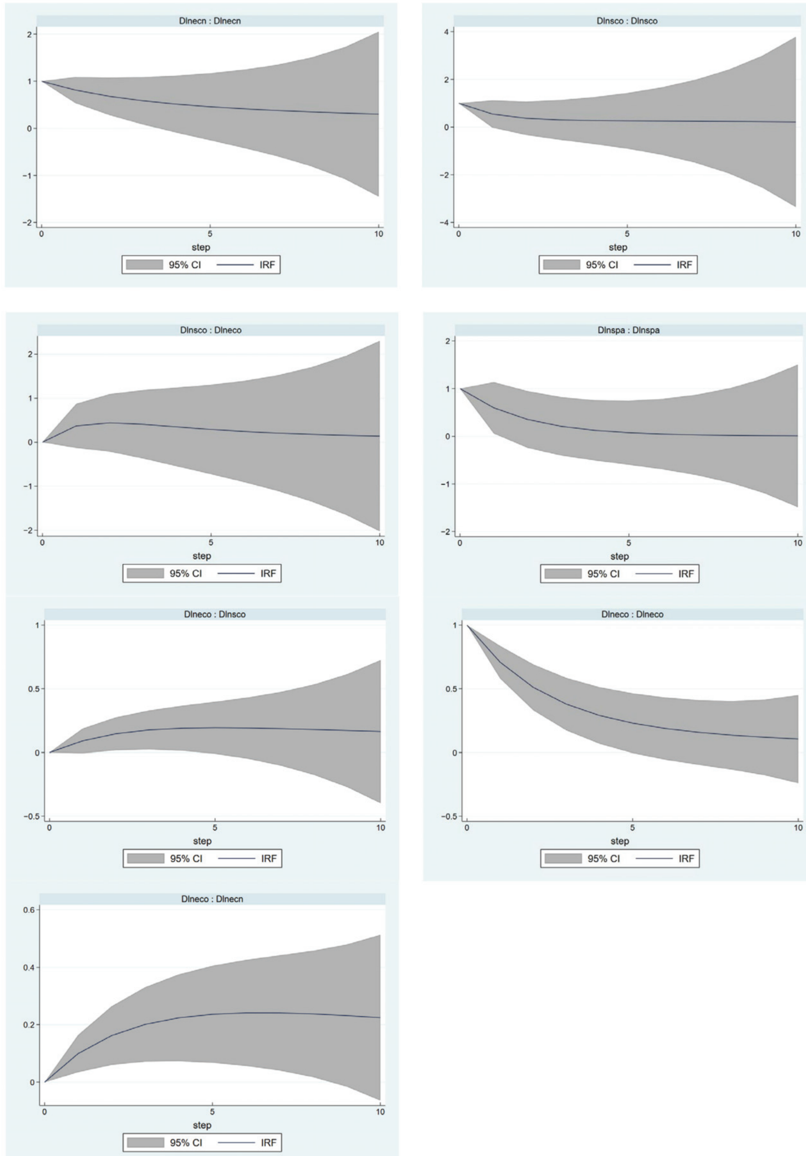

Figure 7. Impulse response diagram for each dimension of urban-rural integration in the Yangtze River Delta.

The impact effect between the variables is then analyzed. The impact of urban-rural ecological integration on urban-rural economic integration is all positive and shows a gradual increase, then gradually decreases and finally falls to zero; it reaches its maximum in the seventh period and then gradually falls to zero after the eighth period. This indicates that urban-rural ecological integration in the Yangtze River Delta region strongly supports urban-rural economic integration, suggesting that the increase in the level of urban-rural ecological integration contributes to the development of urban-rural economic integration. The impact effect of urban-rural social integration on urban-rural ecological integration is also positive, and shows a rapid increase and then a slow convergence to zero; it reaches its maximum in the second period and gradually falls to zero after the fifth period, thus revealing that the increase in the level of urban-rural social integration has a facilitating effect on the development of urban-rural ecological integration. The impact of urban-rural ecological integration on urban-rural social integration is all positive, and slowly rises and then tends to be zero, reaching its maximum in the fourth period and tends to be zero after the sixth period, thus suggesting that the continuous upgrading of urban-rural ecological integration can be beneficial to improve the development level of urban-rural social integration.

5. Discussion

5.1. Analysis of Spatial and Temporal Changes and Dynamic Effects of the Development of Urban-Rural Integration

The urban–rural relationship has been recognized as the most fundamental economic relationship and has always aroused wide attention from scholars. Chinese scholars have primarily focused on the evolution of urban-rural relations, the connotation of urban-rural integration, as well as the development level measurement of urban-rural integration, etc. [13,31]. As the research on urban-rural relations has progressively deepened, the research on the development of urban-rural integration has shifted to the research on spatial and temporal patterns and driving factors [32,33]. Research on the development of urban-rural integration was initiated earlier in developed nations, whereas it has been largely based on qualitative research and approached from a single perspective of primarily urban-rural industrial development and urban-rural public services. Scholars have commonly adopted the method of the multi-indicator evaluation system to measure the level of the development of urban-rural integration, and the selection of indicators usually aims to study the urban-rural system as an organic whole using the comprehensive index method and the coupling and coordination method primarily. In brief, few of the existing studies have analyzed the inner mechanism of the development of urban-rural integration, and previous research tends to neglect the analysis of the dynamic effects between the development of urban-rural integration systems [34,35]. Accordingly, based on the definition of the development of urban-rural integration and the internal evolution mechanism, an evaluation index system is developed in this study for the development of urban-rural integration in four dimensions, including economic-social-spatial-ecological dimensions, the indexes are divided into comprehensive, comparative and driving categories, the inaccuracy caused by the selection of urban-rural indexes focusing only on urban-rural differences and static perspective is corrected, and the spatial and temporal evolution characteristics of the development of urban-rural integration are analyzed from 27 central cities in the Yangtze River Delta region between 2003 and 2020. The Yangtze River Delta region is recognized as a relatively developed region in China in terms of its domestic economic development level, high urbanization level, and comprehensive development level. Thus, the study on urban-rural integration development in this region can provide possible references and lessons for the study on urban-rural relations in developed cities abroad, while providing useful references for urban-rural planning. Furthermore, the study on dynamic impact effects of urban-rural integration and development subsystems can reveal the mechanism of urban-rural development subsystems, and thus provide possible theoretical support for achieving better urban–rural relationships in the future. The spatial and temporal evolution characteristics of the development of urban-rural integration in the 27 central cities of the Yangtze River Delta region between 2003 and 2020 are investigated, followed by a panel vector autoregressive model (PVAR) model to analyze the dynamic impact effects between urban-rural economic integration, urban-rural social integration, urban-rural spatial integration, and urban-rural ecological integration in the Yangtze River Delta region.

First, for the overall time-series change characteristics, the level of the development of urban-rural integration in the Yangtze River Delta region has been elevated between 2003 and 2020, which is significantly correlated with a series of policies implemented in China since 2003, with the aim to boost rural development, including the strategies of integrated urban-rural development, coordinated urban-rural development and new urbanization, which have played a crucial role in achieving the development of urban-rural integration [36]. The conclusion of this study is consistent with the findings of Daizhong Tang et al. [37]. In addition, the increase in the level of the development of urban-rural integration in the Yangtze River Delta between 2019 and 2020 is the smallest compared with other years, primarily due to the shock of the sudden outbreak of the domestic epidemic in China (which began in Wuhan) at the end of 2019. Second, by region, the Yangtze River Delta is one of the most dynamic regional economies in China and one of the most innovative urban agglomerations, whereas its intra-regional urban-rural integration still has significant differences, with the spatial distribution pattern of the Yangtze River Delta region shifting from "low level, low disparity" to "high level, high disparity". These differences are generated because cities (e.g., Shanghai, Suzhou, Wuxi) in the Yangtze River Delta are leading cities in terms of economic development and their strong level of economic development, thus supporting the improvement of their level of the development of urban-rural integration. However, the high degree of interaction between the urban and rural areas in terms of factor flow, industrial interaction and transport and information networks improves their higher level of the development of urban-rural integration [38]. Cities (e.g., Chizhou, Anqing, Chuzhou) are lagging behind other cities in the region in terms of economic development, and the above cities are at the primary stage of urban-rural integration development. Moreover, it is considered that the Yangtze River Delta region has experienced a "northward, southward, and westward" expansion trend over the past few years, and that cities in the region that were originally economically developed (e.g., Shanghai, Suzhou, Wuxi) have become increasingly vulnerable to the development of urban-rural integration. It is also possible that due to the expansion trend of the Yangtze River Delta region recently, the original economically developed cities in the region (e.g., Shanghai, Suzhou, Wuxi) have a more significant siphoning effect on the newly introduced cities and a weaker diffusion effect, thus resulting in a "Matthew effect" of the level of the development of urban-rural integration [39]. Third, as revealed by the dynamic impact effect of urban-rural integration in the Yangtze River Delta region, urban-rural ecological integration plays a positive role in promoting the improvement of urban-rural economic integration and urban-rural social integration [40,41], and the development of urban-rural social integration can promote the improvement of urban-rural ecological integration development. Moreover, the result of this study fills the gap of the study by Changjun Jiang et al. and Daizhong Tang et al. and indicates the mechanism of action between urban-rural integration subsystems [37,42], thus revealing the "high-quality development path oriented to ecological priority and green development" advocated by the Chinese government in recent years [43]. Furthermore, to develop urban-rural social integration, it is crucial to achieve universal sharing of infrastructure and public services between urban and rural areas [44], open up channels for the circulation of factors between urban and rural areas, solidify the social foundation for the development of urban-rural ecological integration, and facilitate urban-rural ecological integration toward a virtuous cycle [45].

5.2. Policy Recommendations to Improve the Integration of Regional Urban and Rural Development

Considering that rural decline is prevalent in nations worldwide, especially in developing nations, rural revitalization has become a vital strategy to solve this problem. Thus, comprehensively promoting the integrated development of urban and rural areas takes on critical significance in accelerating the flow of factors and the rational allocation of resources between urban and rural areas, narrowing the development gap between urban and rural areas, promoting the improvement of the quality of the ecological environment in urban and rural areas, and facilitating the realization of urban-rural equivalence. The specific policy recommendations are presented below.

The following policy recommendations are obtained based on the above findings. First, one must pay attention to regional heterogeneity and formulate a policy for the integrated development of urban and rural areas that promotes classification. The Yangtze River Delta region encompasses a wide range of regions, and the level of economic development in the region shows wide differences. Accordingly, on the one hand, for cities with high levels of economic development in the region (e.g., Shanghai, Suzhou, and Wuxi) in which the spillover effect of cities on the countryside dominates, the focus of the future development of urban-rural integration should be placed on stabilizing the economic development benefits of cities and towns and implementing policies for remedying the shortcomings of rural development, while the construction of basic transport infrastructure should be vigorously developed, and the industrial layout should be a way of the agglomeration of labor, production materials and other factors to increase their radiation and diffusion effects. For cities in the region (e.g., Chizhou, Anqing, and Chuzhou), which are relatively behind in economic development, most of the region remains at the stage of urbanization polarization development, and the focus should be placed on future development of urban-rural integration through the promotion of urbanization. However, we should be wary of the "siphon effect" and "border effect" exerted by the development of polarization to achieve the optimal combination of population distribution, industrial layout, capital allocation and other factors, and boost regional socio-economic development to improve the level of their development of urban-rural integration.

Second, in view of the spatial agglomeration characteristics of the Yangtze River Delta region, which is characterized by "weakness and strength", a regional linkage and coordination mechanism should be built to reconstruct the urban-rural spatial system of the Yangtze River Delta region. On the one hand, the key to the integrated development of urban and rural areas in the Yangtze River Delta lies in breaking the shackles of regional administrative boundaries and forming an effective regional linkage mechanism. The interaction and integration of population, market interconnection and resource sharing in the region will be promoted by different participating bodies (e.g., the government and the market) through the establishment of a precise linkage mechanism between urban and rural areas at the provincial and municipal levels, so as to lead to the coordinated development in the economic, social and spatial aspects in the region and improve the overall level of regional urban-rural integration and development. On the other hand, based on the major strategic context of the current double cycle, the Yangtze River Delta region should take full advantage of the Yangtze River Delta integration strategy in regional development by reconstructing the spatial structure of urban and rural areas and forming a network of close cooperative relationships for intra-regional interconnection and interaction. It is necessary to continuously strengthen the in-depth cooperation between developed cities (e.g., Shanghai, Suzhou, and Wuxi) and less developed cities (e.g., Anqing, Chizhou, and Chuzhou) and deepen the urban and rural governance of the less developed cities in the region. Moreover, it should strengthen the development of industrial clusters in the region, actively use the introduced capital, technology, talents and other elements to promote the optimization and upgrading of the industrial structure, make up for the shortcomings of regional development and improve the level of urban-rural integration and development.

Third, based on the analysis of the dynamic impact effect in the Yangtze River Delta region, it is required to actively explore the effective development mechanism between urban-rural economic integration, social integration, spatial integration and ecological integration among the central cities in the Yangtze River Delta region, boost the coordinated development of the urban-rural economy, society and ecology promoted by urban-rural ecological integration, facilitate the construction of public infrastructure, optimize the environment for the development of urban-industry integration and the equalization of urban-rural services, and theoretically support the improvement of the level of the development of urban-rural integration in the Yangtze River Delta region. On the one hand, based on the role played by urban-rural ecological integration in boosting urban-rural economic and social integration, it is of great significance to strengthen the intensive and economical use of resources, boost the transformation of the regional economy to a development mode with low energy consumption, low pollution and low emissions, and transform the ecological and environmental green advantages of the Yangtze River Delta region into social and economic development benefits continuously. On the other hand, considering the positive effect of urban-rural social integration on urban-rural ecological integration, it is crucial to co-ordinate the integration of urban-rural infrastructure and the sharing of urban-rural public services, accelerate the two-way flow of labor, capital and other factors between urban and rural areas, and lay a social foundation for the development of urban-rural integration.

The realization of integrated urban-rural development relies on the two-way flow of factors between urban and rural areas to achieve an optimal combination of urban and rural resources and factors, thus realizing urban-rural equivalence development. However, from the current perspective, it is still a complex task to study its impact on the integrated development of urban and rural areas from the perspective of factor mobility, which is also the next breakthrough in this study. In addition, although this study has portrayed and analyzed the dynamic effects between the subsystems of urban-rural integrated development, it fails to reveal their intrinsic mechanisms of action, while from the perspective of the scope of the study, further analysis of urban-rural integrated development with counties as the research unit is needed in the future to enhance the depth of the study.

6. Conclusions

This study constructs a relatively comprehensive and scientific evaluation index system for the development of urban-rural integration from "economic", "social", "spatial" and "ecological" levels, based on the connotation and internal mechanism of the development of urban-rural integration. A relatively comprehensive and scientific evaluation index system for development of urban-rural integration is built in four dimensions, and the coefficient of variation and Euclidean distance method are used to measure the evaluation value of the development of urban-rural integration of 27 central cities in the Yangtze River Delta between 2003 and 2020. Finally, an empirical study of the dynamic impact effects between the dimensions of urban-rural integration was conducted using a spatial panel vector autoregression (PVAR) model, with the following findings.

(1) In terms of time-series changes, the overall level of the development of urban-rural integration in the Yangtze River Delta region shows a fluctuating upward trend, undergoing an evolutionary process from severe disorder to moderate disorder to mild disorder; however, the overall development level is low and the regional disparities are more obvious, with the high value regions formed by the cities of Shanghai, Nanjing, Suzhou and Wuxi showing more significant differences from the low value regions formed by the cities of Anqing, Chizhou and Chuzhou.

(2) For spatial distribution patterns, in the study period, a relatively significant agglomeration effect of the level of the development of urban-rural integration has been found in the Yangtze River Delta region, with Shanghai, Suzhou, Wuxi, and Jiaxing as the center. The high value areas of the development of urban-rural integration are largely concentrated in the central and eastern regions and coastal regions, whereas the low value areas are primarily distributed in the western and southwestern regions. The spatial distribution pattern shifts from "low level, low gap" to "high level, high gap", and the spatial agglomeration effect tends to be strengthened from east to west. Shanghai and Anqing are the markers, showing the characteristics of decreasing class distribution, which leads to the spatial agglomeration distribution characteristics of "the weak are always weak, the strong are always strong".

(3) For the analysis of the dynamic shock effect of the development of urban-rural integration, all variables show a continuous positive response to shocks themselves, thus suggesting that the respective variable has a certain path dependence (inertia) on itself, whereas this path dependence varies between variables; urban-rural ecological integration change shocks can facilitate the improvement of the development level of

urban-rural economic integration and urban-rural social integration, as well as urban-rural social integration change shocks. The shocks contribute to the improvement of the level of urban-rural ecological integration.

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Article

An Evaluation of the Development Performance of Small County Towns and Its Influencing Factors: A Case Study of Small Towns in Jiangyin City in the Yangtze River Delta, China

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Abstract: Research on the development performance of small towns is critical for promoting their revitalization, advancing urbanization, and high-quality development and transformation for realizing urban–rural integration. We used the DPSIR-DEA model to study the spatiotemporal evolution process and characteristics of the development performance of 14 small towns within the administrative division of Jiangyin city from 2001 to 2019. We subsequently applied a geographical detector model to analyze the spatiotemporal heterogeneity of the factors influencing the development performance of small towns. The results showed that 2012 was a turning point in the overall development performance index of small towns in Jiangyin, revealing initially decreasing and then increasing trends. The development performance index values of different types of small towns evidenced three trends: a steady increase, a continuous decrease, and an initial decrease followed by an increase. During 2001–2019, the development performance of Jiangyin's small towns reflected a spatial evolution pattern of complete dispersion → small agglomeration → large agglomeration. An optimal spatial pattern comprised an increase in the number of towns demonstrating a high development performance and a decrease in the number of towns with a low development performance. GDP per capita, industrial investments, and construction land density were key influencing factors of development performance, which was mainly driven by economic and social factors, with ecological factors having a relatively weak influence.

Keywords: small towns; development performance evaluation; spatiotemporal evolution; influencing factors; Jiangyin City

1. Introduction

Small towns, which serve as key links between cities and rural areas, play a unique role in the integration of urban and rural areas and the promotion of China's new-type urbanization and rural revitalization initiatives. Moreover, their construction and development directly reflect the overall political, economic, and cultural character of a region [1]. The unique status of small towns and the role they play in urbanization have been one of the main focuses of scholarly attention for a long time. From the traditional research perspective, it is generally believed that small towns lack economic efficiency with their stagnated social-economic development [2–4]. Therefore, it is also questioned whether the big cities, medium cities, or small towns would turn out to be the main driving force of urbanization in the new era, triggering a dispute worldwide, especially in China [5,6]. In the face of such a debate, small town evaluations have been conducted with the aim of exploring the importance of small towns in the urbanization process. The role played by small towns in urbanization in various regions and countries around the world is summarized, and these development models and experiences can also be used as a reference for small towns and urbanization in China. For instance, in Japan and South Korea, the national government has implemented industrial revitalization and construction strategies for rural areas at different times, along with the rise of mega cities and the decline of peripheral fringe areas. The thriving development of small fringe town zones has been developed as a result [7]. In Germany, small- and medium-sized towns represent the main population concentrations and are the mainstay of urbanization. The country focuses on the coordination mechanism of balanced development, with few differences in size between towns and cities and thus the achievement of diversified development [8]. In the evolution of urban society in North America, urban space tends to be territorialized, and urban–rural boundaries are gradually broken. Small town areas with competitive new economic characteristics have attracted a large amount of human capital for settlement due to their good community environment [9], driving local urbanization. In addition, a number of individual-specific evaluation studies have also shown significant value. From functional and network systems of small- and medium-sized towns, an environment could be provided wherein people could feel friendlier and less hectic, and with lower housing costs or with more outdoor activities they would have employment opportunities in different locations compared with cities [10]. Furthermore, from the example of urbanization in Germany Bavaria, and rural areas of South Korea that realized their development through rural in situ urbanization (RISU), some researchers advocate that small towns are the future of urbanization [11]. Therefore, regardless of the research perspective, small towns can bridge the gap between urban and rural areas to effectively promote the quality of urbanization [12].

China's urbanization has been a momentous event that has attracted wide international attention [13]. In March 2014, the Central Committee of the Communist Party of China (CPC) and the State Council jointly released a "National New-type Urbanization Plan (2014–2020)" [14]. This was the first official plan to regard new-type urbanization as a national policy [15], which recommended an urbanization approach with Chinese characteristics for achieving the coordinated development of large, medium, and small cities and of small towns, and for comprehensively improving the quality of urbanization. Small towns have become a hot topic in research focusing on China's new-type urbanization strategy. The evaluation of their development performance is important for assessing the quality of urbanization, while also serving as a useful benchmark for improving the quality of regional urbanization.

The study of performance evaluations has always been a critical concern within academic circles in China and abroad. Performance evaluations entail a consideration of the original performance goals as the study criteria and the application of uniform evaluation standards to ensure an objective, fair, and comprehensive evaluation of the outputs of an organization or project within a certain period of time [16–18]. With the gradual conceptual advancement of performance evaluation systems [19–21], scholars at home and abroad have gradually extended their research fields to cover complex systems, such as towns or cities. They have conducted various studies entailing performance evaluations of urban development. Differing from the performance evaluation of a single project or organization, the evaluation of urban development performance focuses on aspects of the economic, social, spatial, demographic, and environmental efficiency of cities or towns during a specific period of time, providing a concrete way of testing the quality of urban development.

Research on urban performance evaluations outside of China has an older history and covers a wide range of fields, mainly from the perspectives of urban social welfare [22], the industrial structure [23,24], infrastructure allocation efficiency [25,26], and policy and institutional management [27,28]. These studies have focused on topics such as the locations of cities and towns [29,30], spatial structures and scale [31,32], key sectors and industrial clusters [33–36], and ecological performance and sustainable development [37–40]. Research methods have entailed a combination of econometric models, spatial models, and semi-structured interviews [41–44]. In China, studies to assess urban performances have mostly focused on the entire country [45], economic zones [46,47], provinces [48,49], urban agglomerations [50,51], and other spatial levels. Some studies have evaluated operational efficiency at specific levels, including green development efficiency, urban land use efficiency, urbanization efficiency, economic development performance, and industrial efficiency. Others have been aimed at perfecting and innovating the index system used to evaluate urban development performance to improve its scientific basis [52,53]. The research methods used are quantitative as well as qualitative, with qualitative studies mainly centering on discussions of problems and factors influencing urbanization efficiency and policy recommendations to improve urban development efficiency [54,55]. Quantitative studies have mainly centered on data envelopment analysis [45,50] and the use of the comprehensive index method, the gray correlation projection method, and other tools for measuring development performance [56].

In summary, current research on development performance evaluations evidences the following characteristics. First, existing studies on performance evaluations have paid more attention to the study of spatial units at medium and large scales, such as urban agglomerations and the entire country, while neglecting the study of individual small towns. Second, up to now, performance evaluations have mostly targeted a specific aspect of urban development, which can only reflect the performance of specific areas, and have therefore not assessed the overall level of development.

The development performance of small towns is evaluated as an independent composite system of inputs and outputs [57]. It refers to the ratio of the effective outputs of all factors to the overall inputs across diverse economic, social, and ecological fields in the development and construction of small towns under certain conditions of production technology per unit of time. It reflects the effective allocation, rational use, and management of the input resources of small towns in a comprehensive manner [58], concentrating on quality improvements in the development of small towns.

Different views and controversies relating to an understanding of the role and status of small towns have been evident in the implementation of strategies for their development [59,60]. In the actual process of their development, there are also longstanding problems relating to sloppy land use, scattered capital investments, and low development efficiency. The evaluation of small towns' development performance is aimed at improving the quality of their development and optimizing the allocation of resources by using specific technical methods to develop a system of indicators that reflects development performance and by following appropriate procedures to ensure scientific judgments and assessments [61]. Accordingly, targeted, specialized, and featured policy recommendations on the high-quality development of small towns can be made on the basis of the evaluation, which is therefore an important aid for decision making, contributing to improving the level of regional sustainable development and achieving the overall and coordinated development of urban and rural areas.

Southern Jiangsu is one of the core areas of the Yangtze River Delta urban agglomeration. In the 1980s, counties and townships in this area played a leading role in the creation of the nationally acclaimed "Southern Jiangsu Model" through the development of township-based industries and a collective economy and through active participation in market regulation [62]. As one of the birthplaces of the "Southern Jiangsu Model," Jiangyin City has promoted advanced social and economic conditions in small towns and has long evidenced a trend of high-speed development, thus occupying a prominent position in China. A case study conducted in Jiangyin would therefore yield valuable inputs.

Accordingly, in order to understand the impact of the high-quality development of small towns on China's new-type urbanization, we explain the importance of small towns by evaluating their development performance and make relevant policy recommendations based on the results. In this paper, 14 small towns within the administrative division of Jiangyin city, which is located in southern Jiangsu Province, including 9 organic towns, 2 economic and technological development zones, and 3 streets, were selected as the study site. Using the DPSIR-DEA model, we selected various economic, social, and ecological indicators to perform a comprehensive evaluation of the development performance of small towns and to analyze their spatiotemporal evolution. The geographical detector model was also used to identify factors influencing changes in development performance to strengthen the results of the evaluation of small towns and to provide conceptual as well as policy support for the high-quality development of small towns along with guiding inputs on further studies on the development performance of small towns.

2. Materials and Methods

2.1. Study Area

Jiangyin is a riverside port city located in the middle and lower reaches of the Yangtze River in southeastern Jiangsu Province. The city, which is equidistant (150 km) from the two major cities of Nanjing and Shanghai, has an administrative area of 987.5 km^2. Therefore, its location is highly strategic. Jiangyin has a developed economy and has been consistently ranked among the top 2 of China's 100 counties. In 2019, Jiangyin had a registered population of 1,264,100 and a permanent population of 1,653,400, while the regional GDP was 400.112 billion yuan.

A total of 10 organic towns and 7 streets falls under the city's administration. In addition, the Jiangyin High-Tech Development Zone and Jiangyin Harbor Economic Development District, which are township-level administrative units, are under its jurisdiction. The former includes Chengdong Street, while the latter includes streets and organic towns, such as Lingang Street, Shengang Street, Xiagang Street, and the town of Huangtu. For this study, the small towns examined are all defined as township-level administrative units within the jurisdiction of Jiangyin, covering organic towns and streets and economic and technological development zones established through the merger of one or more organic towns. We focused on the economic and technological development zone as a unified research unit in which internal streets and organic towns were merged as the research criteria.

As a result, the research area thus covers two economic and technological development zones, three streets, and nine organic towns within the administrative division of Jiangyin. These areas are: the Jiangyin Harbor Economic Development District (hereinafter referred to as Harbor Development District) and the Jiangyin High-Tech Development Zone (hereinafter referred to as the High-Tech Zone), the streets of Chengjiang, Nanzha, and Yunting, and the towns of Yuecheng, Qingyang, XuXiake, Huashi, Zhouzhuang, Xinqiao, Changjing, Gushan, and Zhutang (Figure 1).

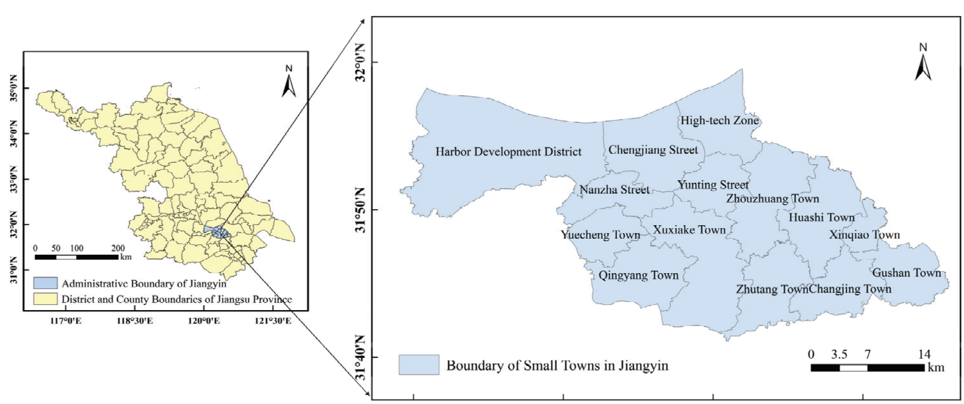


Figure 1. Location of areas covered in Jiangyin City.

2.2. Data Source and Processing

The study data included statistical panel data, remote sensing image data, digital elevation model (DEM) data, and normalized difference vegetation index (NDVI) data, as shown in Table 1. Population, industrial, and related economic and social data were obtained from the Jiangyin Statistical Yearbook and the Jiangyin Yearbook for the years 2001–2019. ArcGIS zoning statistics, spatial interpolation, and raster calculations were used to obtain data on the NDVI index, the green field rate, elevation, river density, and construction land density. Spatial data on changes in small towns relating to the merger and adjustment of administrative divisions were sourced from the latest small town zoning map and dropped onto the corresponding towns. Consequently, a unified base map of the administrative divisions was obtained.

Table 1. Data sources for development performance evaluation indicators in Jiangyin [63–68].

The Data Name	Year	Data Description	Data Sources
DEM Data	2019	Digital elevation model with 30 m spatial resolution	https://www.resdc.cn/data.aspx?DATAID=217/ (last accessed on 8 July 2022)
Land-use Data	2001 2014 2019	Interpretation of remote sensing monitoring data at a 30 m spatial resolution	https://www.resdc.cn/Datalist1.aspx?FieldTyepID=1,3/ (last accessed on 8 July 2022)
River and Lake Datasets	2019	River and lake vector datasets	https://www.resdc.cn/Datalist1.aspx?FieldTyepID=1,3/ (last accessed on 8 July 2022)
Administrative Division Data	2019	Used to extract the study base map	https://www.resdc.cn/data.aspx?DATAID=203/ (last accessed on 8 July 2022)
NDVI Data	2001–2019	Maximum annual NDVI data at a 30 m spatial resolution	http://www.nesdc.org.cn/sdo/detail?id=60f68d757e28174f0e7d8d49/ (last accessed on 8 July 2022)
Statistical Yearbook Data	2001–2019	Demographic, industrial, social, and other statistics	Jiangyin Statistical Yearbook

2.3. Methods

2.3.1. DPSIR-DEA Model

The Driving Forces–Pressure–State–Influence–Response (DPSIR) Model delineates system indicators into five components: driving force, pressure, state, influence, and response. This structured theoretical model is widely used in the evaluation of environmental system indicators [69–71]. It has the advantages of comprehensive content coverage and a strong logic, which can fully reflect the two-way relationship between the system and human activities. Consequently, it provides a scientific theoretical basis for the study and measurement of the elements and attributes of complex systems.

Data Envelopment Analysis (DEA) [72] is used to evaluate the work performance of organizations of the same type and is appropriate for use in the performance evaluation of independent complex systems, such as small towns. Specifically, it enables the relative effectiveness and efficiency of decision-making units (DMUs) with multiple input and output elements to be assessed [73]. An optimal endogenous method is applied to determine the weights of each input factor, avoiding subjective factors that may affect the input–output relationship [74].

The combined DPSIR-DEA model covers all of the relevant indicators, enabling a comprehensive analysis of the interactions between social and cultural factors, economic development, and the natural ecology. Moreover, it provides for an objective and accurate calculation of the development performance of small towns, which facilitates comparisons between different regions and compensates for shortcomings of inefficient regions according to local conditions.

To ensure the scientific quality and rationality of the index system, we constructed a development performance evaluation system for small towns using the DPSIR model. The constant returns to scale (CRS) model within the DEA model was used to measure small towns' development performance. Taking each small town as a DMU, we assumed that there were K towns, each with M input indicators and N output indicators. With x_{km} representing the input of the m^{th} resource of the k^{th} town, and y_{kn} representing the output of the n^{th} resource of the k^{th} town ($k = 1, 2, \ldots, K$; $m = 1, 2, \ldots, M$; $n = 1, 2, \ldots, N$), the i^{th} town was represented in the CRS-based model as follows [75]:

$$\begin{cases} \min\left[` - {''}\left(\bar{e}^T s^- + e^T s^+\right)\right] \\ s.t. \sum_{k=1}^{K} x_{\mathrm{km}} \breve{}_k + s^- = `x_m^i; \sum_{k=1}^{K} y_{kn} \breve{}_k + s^+ = y_n^i \\ 0 \le ` \le 1, \breve{}_k, s^-, s^+ \ge 0, k = 1, \ldots, K \end{cases} \quad (1)$$

In formula (1): θ denotes the development performance index of small towns, λ_k is a weight variable, s^- is a relaxation variable, s^+ is the remaining variable, ε is a non-Archimedean infinitesimal, and $\bar{e}^T = (1, 1, \ldots, 1) \in E^M$ and $e^T = (1, 1, \ldots, 1) \in E^N$ are unit vector spaces. A larger value of θ corresponded to a higher performance level. When $\theta = 1$, this means that the production frontier of a small town is optimal, and its outputs have reached an optimal overall efficiency level relative to its inputs.

2.3.2. Geographical Detector Model

The geographical detector model is a method of statistical analysis used to identify geospatial heterogeneity and reveal the effects of the underlying driving forces [76]. It is an effective method for detecting spatially distributed consistency and causality between two independent interacting variables [77]. The main manifestation is that if the intensity of a factor has a significant consistency or similarity in spatial distribution with the development performance index, it can indicate that this characteristic factor has a significant influence on the development performance index. The degree to which the probe factor X explains the spatial differentiation of Y can be measured by the q-value, which is expressed as follows [78]:

$$q_{X,Y} = 1 - \frac{1}{n\sigma^2{}_Y} \sum_{j=1}^{m} n_{X,i} œ^2{}_{Y_{X,i}} \quad (2)$$

In formula (2): Y denotes the development performance index of a small town, $q_{X,Y}$ is an explanatory power indicator for the development performance index influencing factor X, n is the number of small towns in the study area, m is the number of types of influencing factors, $n_{X,i}$ is the number of small towns within type i for the influencing factor X, $\sigma^2{}_Y$ is the variance in the development performance index of small towns in the study area, and $\sigma^2{}_{Y_{X,i}}$ is the variance in the development performance index of small towns in type i. The value of $q_{X,Y}$ ranges from 0 to 1, and a larger value of $q_{X,Y}$ corresponds to the stronger explanatory power of the X factor regarding the spatial distribution of small towns' development performance.

3. Results and Analysis

3.1. Evaluation of the Development Performance of Small Towns

3.1.1. Construction of the Index System and Weight Analysis

We drew on previous findings derived from the construction of a quantifiable, comparable, and accessible index system [57] in combination with an assessment of the actual situation in the study area. As Table 2 shows, the DPSIR model was used to select 13 indicators from the input and output levels to construct an index system for evaluating the development performance of small towns in Jiangyin. All indicators can be divided into positive and negative indicators according to their attributes. The symbol of "+" in Table 2 represents positive indicators, which means the higher the value, the greater the weight given to the indicator, and the symbol of "−" is just the opposite. The selected indicators covered the economic, social, and natural ecological characteristics of small towns. Input indicators included capital and labor factors and resource elements, constituting the driving force, pressure, and state system layers. Output indicators included the economic scale, income level, and ecological benefits, constituting the influence and response system layers.

Table 2. Index system for evaluating the development performance of small towns in Jiangyin and indicator weights.

System Layer	Subsystem	Indicators	Properties	Weight
Driving Force(D)	Economic development	Total investment in fixed assets (10^8 yuan)	Input indicator (+)	0.10
	Social development	Year-end employed population (10^4 person)	Input indicator (+)	0.08
		Population growth rate (%)	Input indicator (+)	0.14
Pressure(P)	Resource stress	Year-end arable land (acre)	Input indicator (+)	0.02
		Industrial electricity consumption (10^8 kWh)	Input indicator (−)	0.06
Status(S)	Investment and construction	Proportion of employees in the secondary industry (%)	Input indicator (−)	0.04
		Proportion of employees in the tertiary industry (%)	Input indicator (+)	0.05
Influence (I)	Economic quality	GDP growth rate (%)	Output indicator (+)	0.12
	Life quality	Per capita disposable income (yuan).	Output indicator (+)	0.12
Response(R)	Industrial structure	The proportion of the secondary industry (%)	Output indicator (−)	0.10
	Consumption mode	Per capita fixed asset stock (yuan)	Output indicator (+)	0.08
	Ecological resource	Comprehensive energy consumption of industrial enterprises above designated size (tons of standard coal/10^4 yuan)	Output indicator (−)	0.07
		NDVI index	Output indicator (+)	0.02

Indicators were selected according to five systems. The first was a driving force system comprising two subsystems: economic development dynamics and social development dynamics. In this system, total investments in fixed assets reflected the speed and scale of fixed asset development, representing the quality of industrial development in small towns. The year-end employed population and population growth rate reflected the social attractiveness and quality of urbanization [79]. These indicators constitute potential triggers for changes in the development performance of small towns, which, in turn, collectively exert pressure on the system.

The second system was a pressure system composed of a resource pressure subsystem, which represented the pressure on small towns to achieve a green economy and sustainable development, impacting changes in their development status. Year-end arable land reflects the contradiction between land supply and demand and shows the degree of coordination between local construction and the development and protection of arable land resources. Industrial electricity consumption is one of the important indicators for assessing the degree to which new-type industrialization as well as energy conservation and emission reduction are promoted.

The third system was a state system comprising investment and construction status subsystems, which directly affect the economy, society, and natural resource base of small towns. Notably, the proportion of employees in the secondary and tertiary industries reflects the degree of modernization of industries, resulting from the investment of capital and industrial transformations in small towns.

The fourth system was an influence system comprising subsystems of economic quality and life quality, which prompt small towns to take a series of positive measures to respond to changes in the external environment. The GDP growth rate and per capita disposable income are closely related to the wage income level of urban residents, which is the most intuitive embodiment of the development benefits of small towns. It can reflect the degree of progress of small towns in terms of their economic development and social security during a certain period of time.

The fifth system was a response system comprising the following subsystems of responses: the industrial structure, consumption mode, and ecological resources. The proportion of the secondary industry is an important indicator reflecting the rationality of the industrial structure [80,81] and is used to determine the types and patterns of small towns. The per capita fixed asset stock indicates the ability of urban residents to cope with economic risks, directly reflecting consumption patterns, the quality of urban residents' lives, and the level of economic development of small towns. The comprehensive energy consumption of industrial enterprises above a designated size directly reflects the degree of dependence of industrial development on energy resources [82]. The NDVI index [83] covers the crop growth status and ecological vegetation cover. These indicators commonly reflect the response of ecological and energy resources to the construction of small towns.

The entropy method was used to assign weights to each indicator. The results showed that from the perspective of the system layer, the driving force weight was 0.32, the pressure weight was 0.08, the state weight was 0.09, the influence weight was 0.24, and the response weight was 0.27. The driving force, influence, and response systems evidently played influential roles in the development performance of small towns in Jiangyin, mainly in terms of economic and social indicators. The weight of the state system layer was close to the weight of the pressure system, and their degrees of action were comparable.

A total of 5 of the 13 indicators, all of which were economic, industrial, and social indicators, with weights above 0.1 and a total weight of 0.58, had the greatest impact on the development performance of small towns in Jiangyin. The driving force and influence systems occupied two indicators separately. The indicators within these two systems have a significant impact on the development performance of small towns in Jiangyin, revealing that positive measures taken in these towns to promote economic and social development have had positive effects on their development performance such as increased investments, greater talent attraction, and improved incomes.

Our results indicated that there were seven input indicators and six output indicators, evidencing a balance in their numbers. The total weight of all of the input indicators was 0.49, while the total weight of all of the output indicators was 0.51, indicating that the research system has maintained a stable input–output structure over time, revealing the existence of a scientific foundation for the evaluation of the development performance of small towns in Jiangyin.

3.1.2. Analysis of Development Performance Trends

We used the DEAP software, version 2.1, to measure the development performance index of 14 small town units in Jiangyin from 2001 to 2019. Figure 2 depicts the comprehensive development performance index of each town, while Figure 3 shows the development performance trend curve for small towns, which more intuitively reflected the changes in their development performance.

From the overall perspective, the average development performance of small towns in Jiangyin shows a uniform, gradual decreasing trend followed by an increasing trend. Because there was relatively little overall fluctuation, the overall development of small towns in Jiangyin was relatively stable during the period 2001–2019. The average value shows a decrease prior to 2012 and an increase after 2012. The main reasons are as follows. On the one hand, at the turn of the 21st century, when the process of regional globalization was deepening, the external environment for small town development was becoming negative, and the dominant and supporting role of township enterprises was beginning to be questioned [84,85]. Consequently, the traditional "Southern Jiangsu model" gradually fell into decline and went downhill, no longer adapting to the needs of economic development at that time. During this period, the "New Southern Jiangsu Model" that ushered in the transformation had not yet been explored, and the new reform of the economic system was not effective, leading to a gradual decrease in the overall development performance of small towns in Jiangyin in the early 21st century. On the other hand, around 2012, with the development system associated with the New Southern Jiangsu Model reaching maturity, the authorities actively seized the developmental opportunity for advancing the reform of the economic system and management of towns and villages, relying on Shanghai's active leadership role in introducing foreign investments and facilitating traditional township enterprises in upgrading to high-tech industries. During this period, many administrative changes led to the growth of townships, the gradual improvement of industrial parks, and the increasing maturity of featured industries in small towns. At the same time, large quantities of land for construction were available, and economic and social development was reaching a new normal level, revealing the urbanization characterized by capital and manufacturing, along with the construction of development zones being the main driving force. These are the explanations for the trends in the average development performance of small towns.

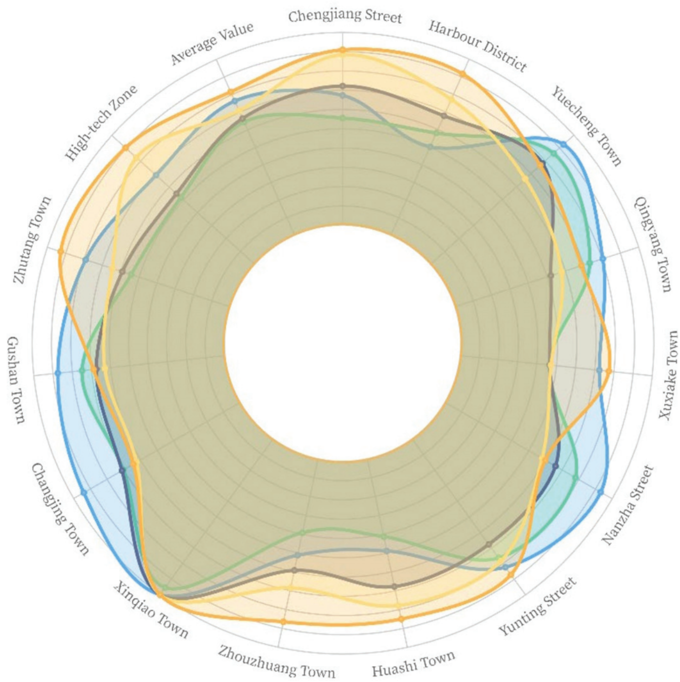


Figure 2. Development performance index of small towns in Jiangyin.

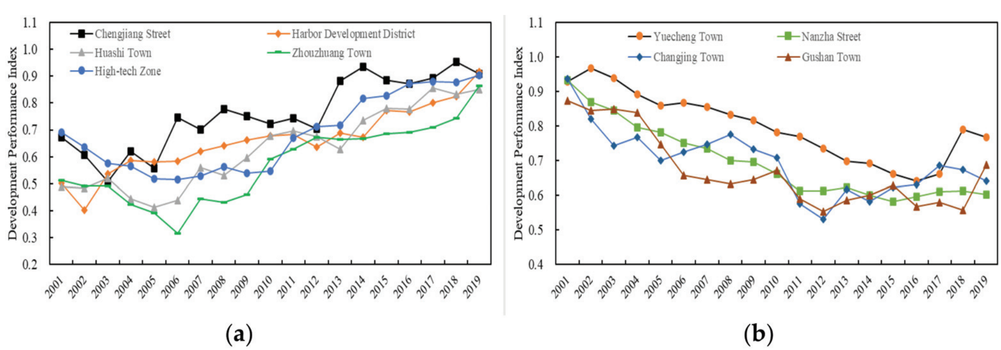
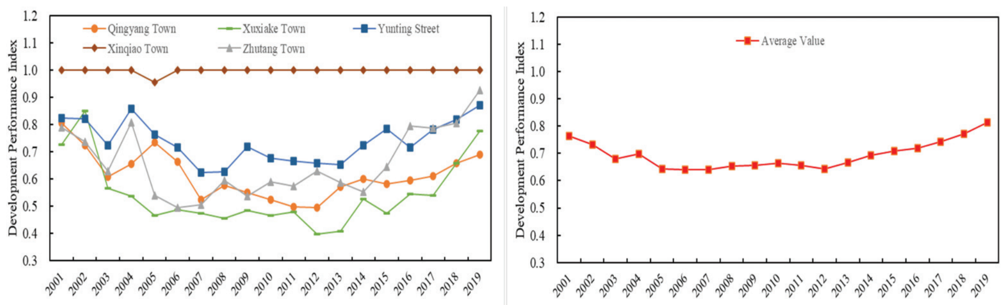


Figure 3. *Cont*.



(**c**) (**d**)

Figure 3. Trends in the development performance of small towns in Jiangyin from 2001 to 2019. (**a**) Overall rise (**b**) Overall decline; (**c**) Initial decrease and then increase (**d**) Trend of average values.

From the perspective of individuals, three trends can be discerned in the development performance of small towns in Jiangyin from 2001 to 2019. The first is a stable overall increasing development performance trend for Chengjiang Street, Harbor Development District, the High-Tech Zone, and the towns of Huashi and Zhouzhuang. Of these areas, Chengjiang Street, Harbor Development District, and the High-Tech Zone are located in or near the central city of Jiangyin, whereas the towns of Huashi and Zhouzhuang are industrial towns located in the eastern part of Jiangyin City. These small towns have conducive conditions for the economy and society, and are strong industrial towns with well-established industrial and service industries, which epitomizes the Southern Jiangsu Model. They merged with neighboring towns during the many administrative changes, and have acquired more resources. Consequently, they are strongly cohesive and expansive in terms of their scale and economic strength, and their development performance is steadily increasing.

The second is an overall decreasing development performance trend for Nanzha Street and the towns of Yuecheng, Changjing, and Gushan. These small towns all have strong eco-agricultural characteristics and beautiful scenery, and are relatively far away from the city center. Moreover, primary industries are more evolutionary in these areas. They mostly developed traditional secondary industries such as the chemical industry and manufacturing, which had certain advantages during the initial process of transitioning into a planned economy. However, they were also limited by their scale and policy support. Consequently, they had not cultivated a good self-generating mechanism and atmosphere for enterprises, resulting in the absence of a long-term driving force to achieve industrial transformation and attract talent and investments. With the gradual improvement of the market economy and intensification of competition, these towns were left behind in the second venture of the township enterprises, resulting in the continuous decrease in their development performance each year.

The third is an initially decreasing and then increasing development performance trend for Yunting Street and the towns of Qingyang, XuXiake, Zhutang, and Xinqiao. The development performance of such small towns is generally similar to the average development performance trend of small towns in Jiangyin, taking 2012 or so as a turning point. These small towns can be divided into two types to explain the reasons for the trends in their development performance.

Yunting Street and the towns of Qingyang and Zhutang are traditional industrial towns dominated by the textile and garment industry and electrical materials. During the initial phase of the 21st century, their total economic volume and social development were positioned at the middle and lower ends for small towns in Jiangyin, and urbanization lagged behind that of other towns. These small towns evidenced economic weaknesses, such as part-time agriculture, a lack of support for tertiary industries, and difficulty obtaining employment. Therefore, a decreasing trend in their development performance was shown. Around 2012, an expansion mechanism for the new industrial zone gradually took shape, generating clusters with competitive advantages, which resulted in an exponential rise in development performance. This shift was, on the one hand, strongly influenced by locational conditions of being close to the city center, in line with the general trend in the regional environment of the transformation and upgrading of industrial structures and reforms of the economic system resulting from the implementation of a favorable policy. On the other hand, it was also driven by the overflow of population, capital, and industrial transfers from developed towns such as Chengjiang Street and the High-Tech Zone.

Cultural tourism is a feature of the town of XuXiake, whose tourism industry is planned, constructed, and integrated with the famous ancient Chinese geographer Xiake Xu as the core figure, with particular cultural attributes. In the early stage of development, the town's tourism attributes were inferior in relation to the surrounding 5A-class scenic spots, which have both historical backgrounds and sightseeing value, notably the ancient town of Zhouzhuang in Suzhou and YuanTouzhu Park in Wuxi. Consequently, the town's ability to attract tourists was relatively weak, leading to a declining development performance. When the "Outline of the Thirteenth Five-Year Plan for the National Economic and Social Development of Jiangyin (2015–2020)" [86] clearly proposed a goal of taking the provincial XuXiake Leisure Tourism Resort as the carrier to achieve the agglomeration and development of tourism projects in the town of XuXiake afterwards, policy support thus turned into development advantages, resulting in the gradual upgrading of rural tourism by promoting the "tourism +" model, such as "tourism + agriculture" or "tourism + manufacturing" and so on, showing an upward trend in its development performance.

It is noteworthy that the town of Xinqiao is the only small town that has maintained its development performance at a value of 1 over a 19-year period. It is the only specialty town in Jiangyin that engages in intensive land use and applies the model of "three concentrations" (land concentration with regards to the scale of the operation, concentration of peasant residences in township areas, and concentration of enterprises in industrial areas). It also let major enterprises play the role of a "bellwether", driving relations of production, cooperation, and competition among medium and micro enterprises. It has ranked first in Jiangyin in terms of its per capita output and per capita profit creation for quite a long time and achieved an efficient balance between resource inputs and outputs.

3.1.3. Spatiotemporal Evolution of Development Performance

In the above analysis, it is apparent that 2012 was a turning point in the change trend for the development performance of small towns in Jiangyin. To show the impact of the measures taken after 2012 as the turning point, we chose the forward year 2014 as the intermediate time point. Therefore, we selected data for 2001, 2014, and 2019 when assessing the combined development performance index of small towns in Jiangyin over the period 2001–2019 by using the natural breakpoint method. Five area types of development performance were used: low-performance areas, relatively low-performance areas, general-performance areas, relatively high-performance areas, and high-performance areas. ArcGIS, version 10.2 was used for spatially visualizing these area types (Figure 4) and for conducting a deeper analysis of the spatiotemporal evolution process.

As Figure 4 shows, in 2001, the central and industrial towns of Chengjiang Street, the Harbor Development District, the High-Tech Zone, and the towns of Zhouzhuang, Huashi, and Xuxiake comprised the low-performance and relatively low-performance areas in 2001, with a wide range of townships situated along the east–west and north–south sides of Jiangyin. Despite having a strong industrial base and a large population and economic scale, these small towns were constrained by technical imitations, a backwards economic structure, and a low resource utilization efficiency that caused them to be unable to transform invested capital, energy, and human resources into high-quality economic and social benefits. The general performance areas were mainly located around areas with high-performance index values (including relatively high-performance areas and high-performance areas), which were traditional industrial towns such as Yunting Street and the towns of Qingyang and Zhutang. These small towns were subject to the industrial undertaking of developed small towns and the outside world, and have certain enterprise bases. However, the land use in the township area was fragmented and unable to capitalize on its development advantages. Areas with high-performance index values were mainly distributed in the southeast and west of Jiangyin, which are far away from the urban area, and are mostly eco-agricultural towns, such as Nanzha Street and towns of Yuecheng, Xinqiao, Changjing, and Gushan. Benefiting from natural environmental resources, these small towns' agricultural industries were more developed, and the continuous development of ecological land, such as farmland and water bodies, resulted in intensive land use in the town area, which was subject to technological changes from an early stage. Higher levels of development performance were evident in areas with less restrictive conditions. In general, the development performance of small towns in Jiangyin in 2001 evidenced a decentralized spatial pattern of "high on both sides and low in the middle".

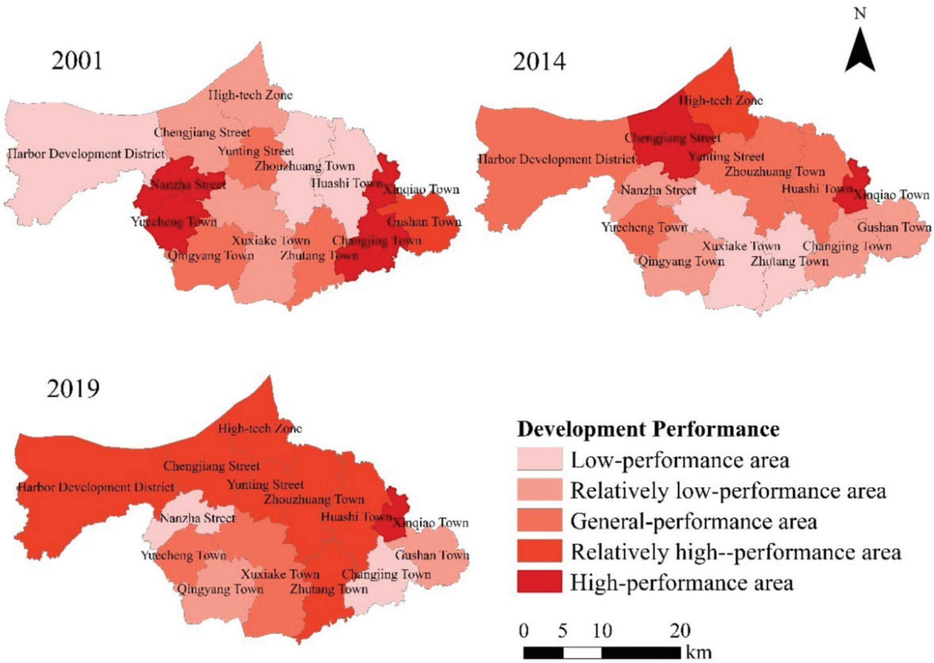


Figure 4. Spatial patterns of the development performance of small towns in Jiangyin from 2001 to 2019.

In 2014, after several rounds of technological innovation and capital introduction had been completed in Jiangyin, the development model changed and the spatial pattern of the development performance of small towns underwent tremendous changes, gradually transforming into a spatial pattern of small clusters decreasing from the northeast to the southwest. During this period, the development performance levels of several small towns changed. Areas such as Chengjiang Street, Harbor Development District, the High-Tech Zone, and the towns of Zhouzhuang and Huashi have been upgraded respectively from low-performance and relatively low-performance areas to areas with general and high development performance index values. All of these towns are located in or near the central area of Jiangyin and are intersected by several major transportation routes. Because of their superior locations and transportation conditions, these small towns maintain close ties in terms of resource allocation and flows. Apart from that, with the rapid progress of science and technology, the limitations on industrial development at the technical level have gradually been compensated for, and the transformation and upgrading of traditional enterprises to high-tech enterprises has effectively improved Jiangyin's development performance. There are also some areas, such as Nanzha Street and the towns of Qingyang, Changjing, and Gushan, which evidenced a decline from being relatively high-performance and high-performance areas to areas with low development performance index values (lower-performance and relatively low-performance areas). Their overall ranking was lower than that of other small towns in Jiangyin, and these towns had natural disadvantages in terms of geographical location and the scale of the townships. They received less support in terms of policies and funds, which led to a gradual widening of the gap with developed towns and the appearance of various development problems.

In 2019, the development performance of small towns in Jiangyin presented the spatial pattern of a large agglomeration that took the north as the pole and was high in the middle and low on both sides. The development performance of small towns ranged from low to high, with the town of Changjing and Nanzha Street as the east and west boundary, separately forming a strong circular agglomeration toward the center. As relatively high- and high-performance areas, Chengjiang Street, Harbor Development District, the High-Tech Zone, the towns of Zhouzhuang, Huashi, and Xinqiao constructed various types of industries in the town parks in proximity to each other, forming a spatial pattern of contiguous development. In fact, the benefits of agglomeration and scale were expanding through a snowball effect during an advantageous cycle. Areas with general performance index values, such as Yunting Street and the towns of XuXiake and Zhutang gradually took off after the transformation that occurred around 2012, and the development pattern at this stage was similar to that of areas such as Chengjiang Street during the previous stage, showing a general positive trend. Small towns in low-performance areas and relatively low-performance areas, such as Nanzha Street and the towns of Changjing, Gushan, and Qingyang were constrained by backward and homogeneous industrial patterns and showed a slow-down in their economic development. The long-term outflow of the population from these small towns led to a lack of impetus to pursue their economic and social development, creating a vicious circle. Moreover, given the size of the township, there is insufficient space for outside industries and an evident fragmentation of the existing industrial land. In the current situation characterized by an unsustainable supply of land and labor and increasing pressure on the environmental carrying capacity, the inertial dependence of traditional development paths has become a huge obstacle to transformation, and the development process of small towns has fallen into a bottleneck.

Overall, from 2001 to 2019, the spatial pattern of the development performance of small towns in Jiangyin evidenced dramatic changes, from a decentralized spatial distribution to an agglomerated spatial distribution. The number of small towns in low-performance and relatively low-performance areas, which were mostly eco-agricultural towns, decreased from 6 in 2001 to 5 in 2019. The number of small towns in high-performance and relatively high-performance areas, most of which were central and strong industrial towns as well as traditional industrial towns that had benefited from certain changes, increased from 5 in 2001 to 8 in 2019. Development levels continued to improve, indicating that the development performance of small towns in Jiangyin achieved optimal spatial patterns.

3.2. Factors Influencing the Development Performance of Small Towns

3.2.1. Analysis of Factor Detection Results

Imbalances in resource endowments and levels of economic and social development affecting each of the small towns in Jiangyin clearly led to spatial heterogeneity in their development performance. To explore the factors accounting for differences in the development performance of small towns in Jiangyin, we selected a total of nine economic, social, and ecological factors considering the profile of the study area and theories of urban systems and urban–rural relationships, as well as the research practices of various scholars who have worked on urban development performance [50–52] (Table 3).

Table 3. Factors influencing the development performance of small towns in Jiangyin.

Influencing Factors	Detection Factors	Factor Interpretation	Unit
Economic factors	X1 GDP per capita	Gross regional product per capita	10^4 Yuan
	X2 Fiscal revenue	Net income from fiscal funds for the whole year	10^8 Yuan
	X3 Industrial investment	Total annual industrial industry capital investment	10^8 Yuan
Social factors	X4 Total social electricity consumption	Sum of the annual electricity consumption of the whole society	10^8 KWH
	X5 Population density	Number of people in unit area	Person/km^2
	X6 Construction land density	Scale of construction land in unit area	%
Ecological factors	X7 Terrain elevation	Average elevation of terrain in the region	m
	X8 River density	Length of the river in unit area	m/km^2
	X9 Greenfield rate	Ratio of greenfield area to total land area	%

Using the factor detection tool in the geographical detector model, we analyzed the degree of influence of each factor on the spatial differentiation of development performances in 2001, 2014, and 2019. The factors passed the significance test at the 0.05 level for each year.

It can be seen from Table 4 that in 2001, industrial investments (X3), with a q-value of 0.7381, had the greatest influence on the development performance of small towns in Jiangyin, while population density (X5) had the least influence, with a q-value of only 0.2829. From a systemic perspective, economic factors have the greatest influence on the development performance of small towns. The significant influencing factors for the development performance of small towns in Jiangyin in 2001 were confirmed by the high rankings of the three economic factors (2nd, 4th, and 1st for X1, X2, and X3, respectively). Both social and ecological factors had a certain degree of influence on development performance, but this influence was not as high, and differences in q-values were not so large, indicating that the effects of social and ecological factors on the development performance of small towns in Jiangyin were similar in 2001.

Table 4. Detection results of factors influencing the development performance of small towns.

Influencing Factors	2001		2014		2019	
	$q_{X,Y}$	$q_{X,Y}$ Ranking	$q_{X,Y}$	$q_{X,Y}$ Ranking	$q_{X,Y}$	$q_{X,Y}$ Ranking
X1	0.4768	2	0.6400	2	0.7661	1
X2	0.4208	4	0.3941	6	0.3761	6
X3	0.7381	1	0.6711	1	0.5794	4
X4	0.3757	7	0.5770	4	0.6588	3
X5	0.2829	9	0.2763	8	0.2242	8
X6	0.4482	3	0.6348	3	0.6600	2
X7	0.3890	6	0.2768	7	0.2115	9
X8	0.3929	5	0.2673	9	0.2830	7
X9	0.3252	8	0.4177	5	0.5229	5

In 2014, industrial investment (X3) was still the most influential factor, with a q-value of 0.6711. The factor with the least influence at this time was river density (X8), with a q-value of 0.2673. Among the economic factors, fiscal revenue (X2) showed decreased influence. Among the social factors, the rankings of all influencing factors improved or remained the same. Conversely, the rankings of the other two ecological factors decreased except for the greenfield rate (X9). This result shows that economic factors should not be the only criteria for determining the final outcome of the comprehensive development performance of small towns. Overall, social factors gained in importance, and scientific and technological progress enabled small towns to overcome various problems relating to natural conditions in the process of development, which led to the consequent decrease in the impact on ecological factors.

In 2019, GDP per capita (X1) was the most influential factor, with a q-value of 0.7661, while terrain elevation (X7) remains the least influential factor, with a q-value of 0.2115. As small towns gradually approached the new normal in the development and transformation process, the rankings of the influence of various economic, social, and ecological factors did not change significantly. This finding indicates that the development performance of small towns was the result of multifactorial influences. Dominance by unilateral factors was impeded, and diversified directions emerged as the main target for the future development of small towns.

3.2.2. Analysis of Interactive Detection Results

We further performed interactive detection on all factors and analyzed the degree of influence of various factors on the spatial patterns of the development performance of small towns in Jiangyin. The results of the analysis are shown in Figure 5. The strengths of the interactions between GDP per capita (X1) and construction land density (X6); industrial investment (X3) and construction land density (X6); total social consumption of electricity (X4) and population density (X5); construction land density (X6) and terrain elevation (X7); and construction land density (X6) and greenfield rate (X9) were all at or near 0.9. These results indicate that the interactions between these factors are consistent with the development performance of small towns in Jiangyin. In particular, the interactions between construction land density and other factors were dominant, indicating that the rational development and utilization of construction land in the context of the actual situation of small towns plays an important role in their development performance. A comparison of the interaction detection results at the three time points revealed that the mean values for the interactions of industrial investment (X3), construction land density (X6), and GDP per capita (X1) with other factors were the highest at 0.7924, 0.7673, and 0.7556, respectively. These results indicated that these three factors critically influence the development performance of small towns in Jiangyin.

The interaction values of industrial investment (X3) and GDP per capita (X1) with other factors were the highest for the degree of improved interaction at 0.0938 and 0.0741, respectively. Therefore, compared with the influence of single factors, the interaction between the two factors and other factors had a greater degree of influence on the spatial differentiation of the development performance of small towns in Jiangyin. The explanatory power of the interaction of the two factors was also stronger than that of the single factor, and the type of interaction among the influencing factors was non-linearly enhanced. This explanatory strength gradually stabilized from 2001 to 2019, indicating that the factors did not exert influences independently of each other. Rather, their influence was characterized by synergistic enhancement, indicating that the development performance of small towns in Jiangyin was the result of the nonlinear coupling of multiple factors.

In general, economic and social factors were the main drivers of the development performance of small towns in Jiangyin, and they were also the main factors influencing spatial variations in their development performance. The degree of influence of ecological factors on the development performance of small towns was relatively weak, mainly because of the impacts of the advancement of science and technology, leading to the gradual weakening of constraints associated with the topography and other natural conditions on the development and construction of small towns. However, the role of ecosystems cannot be completely ignored in the development of small towns, and ecological issues evidently require more attention. The results of the analysis revealed that the importance of the green space ratio is gradually becoming recognized and reflected in the development of small towns. In the future, ecological issues associated with the development of small towns will become increasingly prominent as an important factor determining the ability of small towns to achieve sustainable development.

2001

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
X_1	0.4768*								
X_2	0.8510	0.4208***							
X_3	0.7661	0.7953	0.7381**						
X_4	0.6286	0.8940	0.9340	0.3757**					
X_5	0.7463	0.6791	0.8241	0.9378	0.2829**				
X_6	0.9298	0.7944	0.9593	0.7287	0.7960	0.4482**			
X_7	0.7609	0.6892	0.8022	0.5868	0.4270	0.9798	0.3890*		
X_8	0.6400	0.7086	0.8366	0.6861	0.5512	0.5607	0.5869	0.3929*	
X_9	0.7477	0.5770	0.8790	0.7595	0.9237	0.9807	0.7545	0.8875	0.3252**

2014

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
X_1	0.6400**								
X_2	0.6733	0.3941*							
X_3	0.8891	0.6913	0.6711**						
X_4	0.6684	0.7399	0.8133	0.5770**					
X_5	0.6735	0.6135	0.8527	0.9337	0.2763*				
X_6	0.9387	0.7988	0.9631	0.8100	0.7060	0.6348*			
X_7	0.7142	0.7443	0.7100	0.6728	0.3198	0.9543	0.2768**		
X_8	0.6820	0.5188	0.7443	0.6931	0.5689	0.6399	0.5618	0.2673**	
X_9	0.6677	0.5426	0.7704	0.8307	0.8251	0.8931	0.7133	0.8214	0.4177*

2019

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
X_1	0.7661***								
X_2	0.8013	0.3761**							
X_3	0.8642	0.8121	0.5794**						
X_4	0.9309	0.6437	0.7730	0.6588***					
X_5	0.7638	0.5038	0.6125	0.9383	0.2242***				
X_6	0.8963	0.6840	0.9013	0.8100	0.7846	0.6600**			
X_7	0.7261	0.5639	0.6537	0.6902	0.3155	0.8050	0.2115*		
X_8	0.7406	0.6235	0.7701	0.7051	0.3768	0.7294	0.3354	0.2830*	
X_9	0.8167	0.6303	0.8528	0.8662	0.5521	0.9217	0.5870	0.6753	0.5229*

Single Factor Action   Nonlinear Enhancement

Figure 5. Interactive detection results for factors influencing the development performance of small towns in Jiangyin. * represents significance at the 0.05 level, ** represents significance at the 0.01 level, *** represents significance at the 0.001 level.

4. Discussion

Taking Jiangyin City as our study area, we analyzed the development performance and spatiotemporal evolution characteristics of small towns in a developed county in the Yangtze River Delta. Moreover, we explored the factors influencing their development performance, thus addressing an existing gap in research on the development performance of small towns at this scale. The findings of this study are of referential and innovative value.

4.1. Reliability of Research Results

The DPSIR-DEA model applied in this study combines the advantages of the DPSIR and DEA models and has great scientificity in the construction of the index system and the measurement of development performance index values. From the research results, it is evident that the development performance trends of small towns in Jiangyin and in the coordinated development of industrialization and urbanization in Jiangyin County [87] have been relatively consistent. In both cases, 2012 marked a turning point in the towns' development, which subsequently showed a trend of continuous improvement. The results for our evaluation of the development performance of the town of Xinqiao were strongly consistent with those of a previous evaluation of the town's sustainable development [88], which confirms the reliability of this study. In addition, there are also related studies that have been conducted on the efficiency of a sample of towns in Jiangsu Province, of which the findings indicated that significant differences do exist in the efficiency characteristics of different types of towns, and the economic development level, input–output efficiency and economic density can be high in small towns [12]. Their research findings are certainly highly consistent with the findings of our study. It also proves that small towns can play an important role in integrating urban and rural development, accelerating new-type urbanization, and promoting a rural vitalization strategy. In terms of the high-quality development of small towns, some studies also concluded that the agglomeration economy, place-based specialization, industrial value creation, and state-led platform urbanism at the small-town-like scale have been positioned at the core of the small town strategy [89,90], which is similar to the analysis of this paper, that small towns need to transform and innovate in industry and policy. Following the policy reform and ongoing innovations in science and technology, small towns in Jiangyin will undergo further transformations in their economic and social development in the future, thus achieving the goal of high-quality development. Moreover, the variability in their development performance associated with spatial distribution will gradually decrease, and their development will shift from being scale-oriented to becoming performance-oriented.

4.2. Factors Influencing the Development Performance of Small Towns

This study incorporates economic development zones into the concept of "small towns", thus introducing an innovation into the study of small towns. There are three reasons for this approach. First, economic development zones have been incorporated into the development plans of small towns in most parts of China, and their spatial as well as economic and social development dimensions have long been considered important. Second, because of their wide coverage, economic development zones often contain several contiguous towns, which are highly consistent in terms of their industrial structures and available policy support. Consequently, their overall development levels do not vary greatly. Therefore, as comprehensive representations of the development status of small towns within a continuous territory, economic development zones should be considered as an appropriate research unit. As one of the developed cities in southern Jiangsu, Jiangyin plays an important role as a leader in the development of small towns and shows distinctive characteristics associated with its current economic structure and policy system that are superior for future town planning and development in the national context. Therefore, a third reason for the selection of an economic development zone as a research unit relating to small towns is that it more accurately reflects the actual development of Jiangyin at the local level and has practical implications.

Because of limitations in accessing some data, the indicators for small towns' development performance and influencing factors selected at the ecological level were inadequate. Consequently, the influence of ecological factors on the development performance index values of small towns in Jiangyin was not apparent. Compared with their actual development, there may have been some errors caused by these factors, which need to be augmented in the future. In addition, this study was premised on an objective standpoint and did not take into account the subjective wishes of town residents. In a future study, we will include subjective indicators, such as residents' happiness, by incorporating semi-structured interviews and other research methods within a more in-depth study.

4.3. Policy Recommendations

The following recommendations emerged from our findings. First, at the political dimension, the designation of a new-type city in China named a "county-serviced city" (CSC, xian guan shi) [91] can be advocated for qualified small towns within the existing administrative hierarchy. In the CSC model, small towns would get the same rights as all other large cities in China in dealing with their economic and political development, while maintaining their current position as a township unit in the administrative system and continuing to be served with social service public goods by their county government. Small towns in Jiangyin thus can gain enough autonomy in selling land, planning their future, and managing their development to meet some of the opportunities and challenges they will likely face. We can also learn from the management models of Japan and Germany, where small towns can have autonomy in matters directly related to the daily lives of their residents, including education, welfare, health, finance, etc. [92,93] Moreover, policies directed at the developmental level and bit order of small towns should be formulated scientifically and rationally, and the development target positioning of different types of small towns should be clarified. The policy advantages of small towns with high development performance index values, such as Chengjiang Street, Harbor Development District, and the towns of Huashi and Xinqiao should be further strengthened to make them become the growth poles of small towns in Jiangyin. For small towns with general development performance index values such as Yunting Street and the town of Zhutang, system reforms and the strengthening of industrial supports should be actively implemented. For small towns with low development performance index values such as the towns of Changjing and Gushan, the policy compensation and support via funding and resources should be increased to accelerate a transformation through the mechanism of strong towns driving weak towns.

Second, considering the economic dimension, it is important that small towns with high development performance index values play a leading role in the gradual construction of an environmentally friendly industrial system guided by the concept of a circular economy. At present, some developed areas, such as Chengjiang Street, the High-Tech Zone, and the town of Xinqiao have implemented several initiatives to optimize and transform their industrial structure. However, in general, industry remains dominant in the economic development of small towns in Jiangyin. As the role of ecological factors in the development performance of small towns becomes increasingly prominent, it is necessary to grasp the degree of pollution emissions when introducing new industrial projects. Moreover, large-scale land expansion for economic construction should be stopped. Small towns with low development performance index values and optimal natural resource conditions can also develop ecological agriculture, leisure tourism, and other industries in combination, drawing on the "tourism +" development model implemented in the town of XuXiake to improve land use efficiency.

Finally, with regard to the social dimension, since many small towns other than Chengjiang Street do not have correspondingly perfect public transportation systems between each other, it is necessary to strengthen infrastructure development in small towns and improve the three levels of public transportation networks: urban, town, and inter-district bus systems. In addition, the social environment should also be taken into account, as careful design and manning of the townscape [94], for example, through wide streets and artificially shaped trees, can represent the modern town image. If small towns in economically developed areas such as Jiangyin can take the lead, they will serve as models for other regions and will have a significant impact on the development and transformation of small towns nationwide.

5. Conclusions

For this study, we selected 14 small towns in Jiangyin as the research units to study their development performance and influencing factors. The main conclusions of the study are presented as followed.

During the period from 2001–2019, the overall development performance of small towns in Jiangyin first decreased and then increased, with 2012 marking a turning point. From an individual perspective, the development performance showed three trends, which are a stable overall increasing trend, an overall decreasing trend, and an initially decreasing and then increasing trend, respectively.

Our findings on the spatial evolution pattern from 2001 to 2019 revealed a fluctuating ascending process of complete dispersion → small agglomeration → large agglomeration, associated with the development performance index values of small towns in Jiangyin, which showed an optimized spatial pattern.

Lastly, GDP per capita, industrial investment, and construction land density were the main factors affecting the heterogeneous spatiotemporal evolution of small towns in Jiangyin. Economic and social factors had a strong driving effect on the development performance index values of small towns in Jiangyin and were the main factors influencing the spatial heterogeneity of these values. Ecological issues should receive constant attention in the future development of small towns.

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On the Optimal Allocation of Urban and Rural Land Resources in Rapidly Urbanizing Areas of the Yangtze River Delta, China: A Case Study of the Nanjing Jiangbei New Area

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Abstract: In the process of rapid urbanization, the coordination of the population–land relationship, the optimal allocation of land resources, and the improvement in land-use efficiency are the keys to ensuring the sustainable development of the region. This study takes the Nanjing Jiangbei New Area (NJNA), a national development zone in China, as a case study to construct an analytical framework for the regional population–land–industry (PLI) coupling coordination relationship. A spatial organization model of population–land (PL) flow is used to calculate the coupling coordination degree of PLI factors. The allocation of land resources is adjusted and optimized through the characteristics of the actual population served in the area to determine the new urban population that can be effectively accommodated by the new district. The comprehensive evaluation of the coordination degree of PLI coupling shows that the area connected with Jiangpu and Dacang Street has high development potential in terms of population concentration and construction land layout and can be used as a key area for future development. Based on the analysis of the spatial layout of the PL flow, further suggestions are made to optimize planning for the future population concentration area in NJNA. This study can also provide a reference for the optimal management of land resources in similar areas at home and abroad.

Keywords: rapid urbanization; land resources; optimal allocation; coupling coordination; Nanjing Jiangbei New Area

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1. Introduction

Land is the material basis for the survival and development of human society and an important foundation for sustainable social and economic development. With the continuous acceleration of global industrialization and urbanization, problems such as land nonagriculturalization, land ecological deterioration, and low land-use efficiency have become important constraints on regional sustainable development, and achieving sustainable land use has become an important issue of global concern [1–3]. The optimal allocation of land resources refers to the rational allocation of a certain amount of land resources on the basis of the characteristics of the land and the use of scientific and technological and management tools to achieve sustainable land resource use, which is an important guarantee for the sustainable development of the national economy [4,5]. Scientific, rational, and effective land-use patterns are important aspects of alleviating resource, population, and environmental problems [6]. From the publication of Our Common Future in 1987 to the release of Agenda 21 at the World Conference on Environment and Development in 1992, the new philosophy of sustainable development has been largely accepted worldwide [7,8], and achieving sustainable land resource use and management has become a common goal of all countries in the new era. At the same time, population movement, as an important driving force triggering changes in demand for land resources, profoundly affects regional economic and social development [9]. With accelerated urbanization in China, the combination of the scarcity of land resources and the inefficient allocation of land resources has become a core issue [10]. Therefore, it is necessary to analyse the coupling of population movement and the land's carrying capacity, coordinate the orderly movement of the population, and reasonably allocate land resources to ensure the rational use of land resources and the healthy and sustainable development of the regional economy and society. Since 2018, the integrated development of the Yangtze River Delta (YRD) has been a national strategy in China. As an economically developed and densely populated region, the YRD is a model and a forerunner of urbanization in most regions of China [11,12]. As a world-class urban agglomeration, the YRD region has realized rapid economic, population, and industrial agglomeration through rapid industrialization and urbanization [13,14], resulting in considerable development achievements. The YRD region is at the forefront among regions in China [2], especially at the level of development zones and new areas, serving as an example for other urbanizing areas. However, the industrial-development-oriented model of development zones and new areas is accompanied by high population and economic densities, as well as high resource and environmental pressure in the region, causing new areas within the YRD to suffer from a variety of problems and incongruities, such as tight land resource constraints, unbalanced urban—rural development, and population–land (PL) misallocation [15]. In new urbanization, it is necessary to coordinate the PL relationship, promote the optimal allocation of urban and rural land resources, and improve land-use efficiency [16–18]. In view of the social nature of humans and the spatial variability in population flow, how are population flows coordinated and optimized, the allocation of land resource factors optimized, space utilization efficiency utilized, and integrated urban—rural development coordinated in the typical regional process of rapid urbanization? This question needs to be further answered from both theoretical and practical perspectives, and it is necessary to strengthen research and start addressing the problem, especially at the level of new national areas with an exemplary and leading role in regional development. Therefore, this study analyses the coordination degree of population–land–industry (PLI) coupling in rapidly urbanizing regions, constructs a model to measure the threshold value of urban and rural construction land scales, builds a spatial organization model of PL flow based on population flow data, and conducts spatial overlay analysis. The model is based on population flow data, and a spatial organization model of PL flow is constructed for spatial overlay analysis. The model can identify the coordination between population flow and land-use allocation more clearly by combining the regional population flow situation and then propose differential allocation of construction land indicators, which is expected to provide spatial analysis support for optimizing the spatial layout of regional urban and rural land resources.

2. Literature Review

The optimal allocation of land use has received increasingly widespread attention as an important issue in regional sustainable development. In recent years, researchers have conducted in-depth studies on the coupling of land use and the ecological environment, the optimization of land-use structure, and the comprehensive evaluation of land use [19]. The main areas of research on the optimal allocation of land resources by researchers outside China involve the mechanisms of urbanization, agricultural development, and optimal land allocation [20–22]; the allocation of land resources under different land-use patterns; the optimal allocation of land use for industries, such as agriculture, forestry, and transportation [23,24]; and land-use policies and their role in land-use allocation [25,26]. These studies cover a wide range of areas, provide in-depth investigations, and are conducted with advanced technical means. Some countries have achieved optimal land resource allocation by formulating countermeasures to address land-use problems in urbanization. For example, the United Kingdom focuses on the development of small towns to alleviate the population pressure faced by large cities, thereby mitigating construction land expansion in large cities [27,28]; Israel and the United States prefer to guide the development of small towns by formulating relevant plans that are scientifically sound and sustainable; and South Korea has developed a 10-year comprehensive plan for supporting small towns to address, to some extent, the problems of rural hollowing out and the increasing imbalance between urban and rural development [29,30]. Regarding research by Chinese scholars on the optimal allocation of land use, the basic theoretical research on land evaluations, land-use planning, land-use system engineering, and urban land grading and valuation has been continuously deepened, and land-use research fields have gradually expanded to include, for example, agriculture, forestry, and animal husbandry land; urban land; rural residential land; and tourism land. Methods for the optimal allocation of land resources can be divided into "top-down" and "bottom-up" models [31]. "Top-down" models focus on the overall situation in a region and obtain a series of optimal solutions by considering the global objectives of the region; however, it is difficult for this approach to reflect the evolutionary pattern of microscale spaces and the decision-making process. In comparison, the "bottom-up" model tends to simulate the multiagent decision-making process at the microscale, focusing on the detailed expression of local characteristics, but it is difficult for this approach to meet global multiobjective optimization requirements. For example, Chuvieco combined the linear programming model as a geospatial modelling tool with a geographic information system (GIS) to study the Mediterranean coastal region of Spain with the lowest rural unemployment rate as the objective function to achieve land-use optimization; Ma et al. applied the particle swarm optimization (PSO) algorithm to simulate the optimization of the spatial structure of land use with real datasets, and their results showed that the PSO model has the ability to optimize the quantity and spatial structure of land use [32]. Overall, most models are limited to the optimization of the quantity or spatial structure of land use alone; there is still a lack of research on the coupling and correlation of populations, with factors such as land and industry leading to optimization results that do not match the actual development needs and cannot fundamentally solve the contradiction between population and industrial development on land resource demand. Considering that the optimal allocation of land resources is a complex system engineering problem involving a multiobjective and multilevel continuous fitting and decision-making process, it is necessary to realize the optimal allocation of land resources by constructing a model. Therefore, by coupling and correlating regional population, land, and industry elements; analysing the coordination among regional population flow, land supply, and industrial development demand; and putting forward optimization suggestions accordingly, the conflicts between population, land, and industrial development can be alleviated to a certain extent, which is of great value for improving regional land resource efficiency.

3. Study Area and Methods

3.1. Overview of the Study Area

China's development zones can be divided into two categories. The first category is approved by China's State Council and comprises the national-level development zones, including economic and technological development zones, high-tech industrial development zones, bonded zones, export processing zones, border economic cooperation zones, and other types of development zones. The second category consists of the provincial-level development zones approved by the provincial people's governments, which are divided into provincial-level economic development zones, provincial-level high-tech industrial parks, and provincial-level special industrial parks. Nanjing Jiangbei New Area (NJNA) was approved by the State Council of China on 27 June 2015 and is the 13th national-level development zone in China and the first in Jiangsu Province (Figure 1). It is located in the city of Nanjing, Jiangsu Province, and to the north of the Yangtze River, including the administrative areas of Pukou and Liuhe Districts and the Baguazhou Subdistrict of Qixia District, with a planned area of 788 km^2. The current construction land area is 152 square kilometres, accounting for 39.35% of the total land area; the other construction land area is 13.6 square kilometres, accounting for 3.53% of the total land area; and the non-construction land area is 220.6 square kilometres, accounting for 57.12% of the total land area. NJNA is situated at the intersection of the coastal economic belt and the Yangtze River Economic Belt, as well as at the juncture of the Yangtze River golden waterway and the Beijing–Shanghai Railway, connecting the south to the north and the river to the sea, exhibiting remarkable locational advantages. The official approval of NJNA is highly valuable to the development and layout optimization of China's regional productivity, as well as to the implementation of regional coordinated development strategies. NJNA is the first national new area in Jiangsu Province and serves as an important hub. According to the State Council and the National Development and Reform Commission, NJNA is functionally positioned as "a pioneering area of independent innovation, a demonstration area of new-type urbanization, a modern industrial agglomeration area in the YRD region, and an important platform for opening up and cooperation in the Yangtze River Economic Belt" ("three areas and one platform"). To implement the development strategy for the Yangtze River Economic Belt and the integrated development strategy for the YRD, the development of NJNA must adhere to people-centred urbanization, coordinate the increase in urban population settlement and the growth in urban construction land in the new area, promote the construction of new Jiangsu with a "strong economy, rich people, beautiful environment, and high level of social civilization," and increase the urban primacy index of Nanjing. NJNA is an important urban—rural connection area in Nanjing, a growth pole and main arena of economic development in Nanjing, and a new downtown area and space for urban construction. Taking NJNA as an example to explore the optimal allocation of urban and rural land resources not only helps enhance the overall development potential and capacity of Nanjing but also provides an important driver for the optimal allocation of land resources in other new areas.

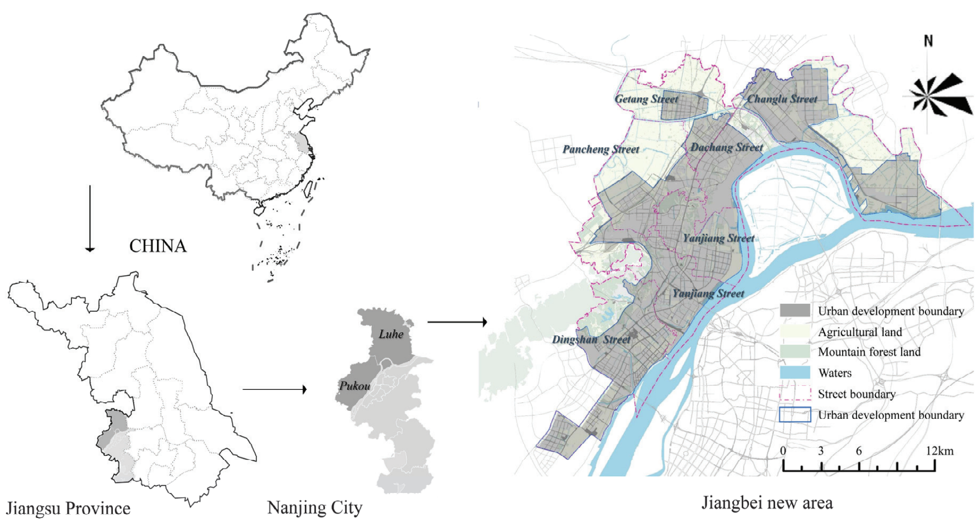


Figure 1. The study area.

3.2. Research Framework and Methods

3.2.1. Research Design and Framework

In this work, one of China's national new areas (NJNA) is used as a case study to analyse the regional PLI coupling coordination relationship, construct a spatial organization model of PL flow, calculate the coupling coordination degree of PLI factors, and analyse the efficiency of resource allocation at a spatial scale. Based on the spatial flow of populations in the region, the limits of existing administrative jurisdictions on land-use planning quotas and planning space allocation are broken. The land demand associated with population flows is generated based on the flow of geographic factors. On this basis, in this study, the spatial demand for land use generated by population flows is analysed, the spatial allocation and transfer of land resources are carried out and promoted, the agglomeration and diffusion of population and land resource factors are realized, and a spatial organization model of PL flow is constructed. This study contributes to expanding the theoretical knowledge and methodological ideas for research on the optimal allocation of urban and rural land resources under new-type urbanization (Figure 2). The specific process is as follows. (1) Analysis of the PLI coupling coordination degree of rapid urbanization areas and agricultural production concentration areas. The population urbanization rate, land urbanization rate, and nonagricultural industry development rate are used to represent the specific quantitative PLI indicators for rapid urbanization areas. The emigration rate of agricultural populations, the reduction rate of rural construction land (reclamation of rural settlements), the development rate of the primary industry, and the growth rate of rural income are used as specific quantitative PLI indicators for agricultural production concentration areas. The PLI coupling degree of rapid urbanization areas and agricultural production areas is input into the model analysis, and, using a coupling coordination degree model, the PLI relationship is expressed by the degree of interrelation and coordination of indicators. (2) Spatial optimization of planning implemented based on the PL linkage. Big data of mobile phone signalling are used to calculate the population actually served and the migrant population, based on which the spatial measurement and spatial overlay analysis of PL flow are carried out to propose a guiding strategy for optimizing the spatial layout of urban construction land.

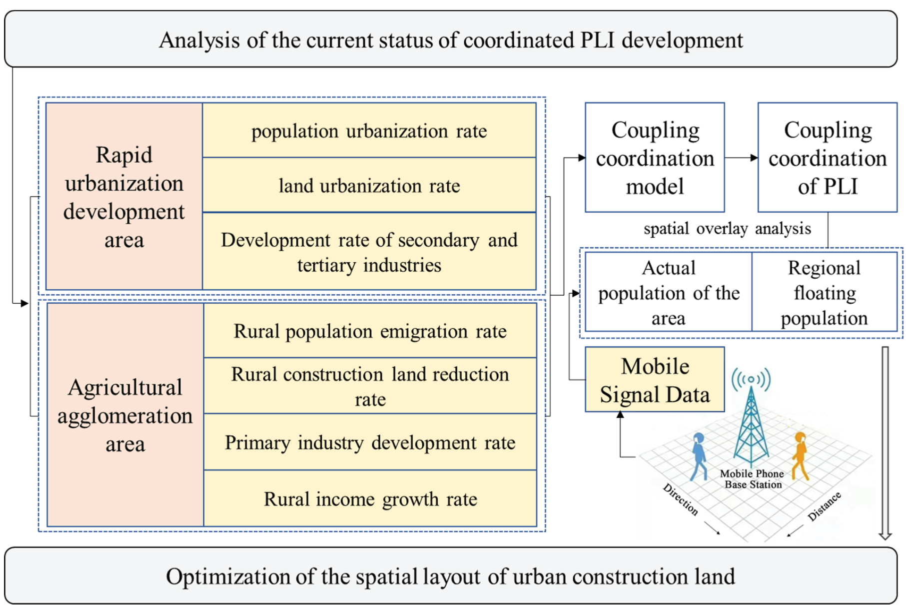


Figure 2. Research design and methods.

3.2.2. PLI Coupling Coordination Analysis

Coupling coordination analysis originated from the related concepts and theories of physical electronics. In this study, population, land resources, and economic development are treated as interrelated systems to construct a coupling coordination degree model and to simulate and analyse the degree of coordination and coupling of factors within two (or more) systems. With reference to relevant research results, PLI coupling is divided into four types based on degree and status [33,34]. The C value reflects the coupling degree of population, land, and economic and industrial development and is taken in the range of [0, 1]. The larger the *C* value is, the higher the degree of mutual coupling and coordination among the factors. Conversely, the smaller the *D* value is, the more the coupled system evolves in the direction of dysfunction and disorder. Referring to relevant research, the equilibrium distribution function method is used to divide the value of the PLI coupling coordination degree into 10 consecutive intervals to determine different coupling coordination statuses [35,36]. The *H* value represents the comprehensive evaluation index (Table 1) and is taken in the range of [0, 1]. Referring to relevant research, an *H* value in the range of [0–0.4] is defined as a low degree of coupling coordination, representing low coupling coordination among population, land, and industrial nonagriculturalization, with primary industry accounting for a certain proportion, relatively lagging industrialization and urbanization, and a low scale and rate of conversion of agricultural land to construction land. An *H* value in the range of [0.4–0.7] is defined as a moderate degree of coupling coordination, meaning that the coupling coordination among population, land, and industrial nonagriculturalization is at a moderate level and the population gradually becomes concentrated during the process of urbanization and industrialization. An *H* value in the range of [0.7–1] is defined as a high degree of coupling coordination, indicating that, with the rapid development of the regional economy, industrial agglomeration, transformation, and upgrading promote a significant increase in urbanization and a large, concentrated population, which provides labour sources for different levels of services, while a large amount of agricultural land is converted to construction land, and urban land expands spatially at a high intensity [17].

Table 1. Classification of PLI coupling coordination.

Type	Coupling Type	Interval	Coupling Status
Coupling degree *C*	Low coupling	0–0.3	There is a weak correlation and low interaction between factors.
	Running-in conflict	0.3–0.5	Factors are intertwined, conflicting, and synergistic.
	Moderate coupling	0.5–0.8	Factors constantly adapt to and influence each other.
	High coupling	0.8–1.0	Factors closely exist and interact with each other.
Coupling coordination degree *H*	Disorderly	0–0.1	The allocation of PLI factors is extremely unbalanced and disorderly.
		0.1–0.2	The allocation of PLI factors is severely unbalanced and disorderly.
		0.2–0.3	The allocation of PLI factors is relatively severely unbalanced and disorderly.
	Running-in	0.3–0.4	The allocation of PLI factors is relatively unbalanced and disorderly.
		0.4–0.5	The allocation of PLI factors is in an unbalanced and disorderly state.
		0.5–0.6	The allocation of PLI factors is basically balanced and orderly.
		0.6–0.7	The allocation of PLI factors is initially systematic, balanced, and orderly.
	Coordinated	0.7–0.8	The allocation of PLI factors is generally systematic, balanced, and orderly.
		0.8–0.9	The allocation of PLI factors is relatively systematic, balanced, and orderly.
		0.9–1.0	The allocation of PLI factors is systematic, balanced, and orderly.

The population urbanization rate, land urbanization rate, and nonagricultural industry development rate are used to represent the specific quantitative indicators of PLI in rapid urbanization areas. The PLI coupling coordination degree of rapid urbanization areas is calculated as follows:

$$C_1 = 3 \times \left[\frac{U_i \times L_i \times D_i}{(U_i + L_i + D_i)^3} \right]^{\frac{1}{3}} \tag{1}$$

$$H_1 = \sqrt{C_1 \times T_1},\ T_1 = \alpha U + \rho L + \gamma D \tag{2}$$

where C_1 represents the degree of coupling, H_1 denotes the degree of coupling coordination, and T_1 is the comprehensive evaluation index of population, land urbanization, and industrial nonagriculturalization; *a*, *q*, and *r* are coefficients to be determined; *a* = *r* = 0.4, and *q* = 0.2. $U_i = PU_i/P_i$ is the population urbanization rate, with PU_i and P_i representing the urban population and the total regional population, respectively; $L_i = LU_i/L$ is the land urbanization rate, with LU_i and L denoting the area of urban construction land and the total regional land area, respectively; and $D_i = (SGDP_i + TGDP_i)/GDP_i$ is the nonagricultural industry development rate, with $SGDP_i$ and $TGDP_i$ representing the added values of the secondary and tertiary industries, respectively; while GDP_i denotes the gross domestic product and *i* represents the study unit.

The specific quantitative indicators of PLI are represented by the emigration rate of agricultural population, the reduction rate of rural construction land (reclamation of rural settlements), the development rate of primary industry, and the growth rate of rural income. The coupling coordination degree of agricultural production concentration areas is calculated as follows:

$$C_2 = 4 \times \left[\frac{Ji \times Lui \times Fi \times Si}{(Ji + Lui + Fi + Si)^4} \right]^{\frac{1}{4}} \tag{3}$$

$$H_2 = \sqrt{C_2 \times T_2},\ T_2 = \alpha J + \beta L + \gamma F + gS \tag{4}$$

where C_2 is the degree of coupling; H_2 is the degree of coupling coordination; T_2 is the comprehensive evaluation index for the emigration rate of the agricultural population, the reduction rate of rural construction land (reclamation of rural settlements), the development rate of the primary industry, and the growth rate of rural income; and *a*, *q*, *r*, and *g* are the corresponding coefficients to be determined. Because the emigration rate of the agricultural population, the development rate of the primary industry, and the growth rate of rural income are equally important, *a* = *r* = 0.3 and *q* = *g* = 0.2. $N_i = (P_i - P_0)/P_i$ is the emigration rate of the agricultural population, with P_0 and P_i representing the agricultural population of the region in 2015 and 2018, respectively; $J_i = (JU_0 - JUI_i)/JU_0$ is the reduction rate of rural construction land, with JU_0 and JU_i denoting the rural construction land of the region in 2015 and 2018, respectively; $F_i = (FGDP_i - FGDP_0)/FGDP_0$ is the development rate of the primary industry, with $FGDP_0$ and $FGDP_i$ representing the added value of the primary industry in the region in 2015 and 2018, respectively; and $S_i = (S_i - S_0)/S_0$ is the growth rate of rural income, with S_0 and S_i representing the rural net disposable income in the region in 2015 and 2018, respectively.

3.2.3. Method for Spatial Optimization of Planning Implemented Based on the PL Linkage

Population flow refers to the migration of a population from a certain region to another. Tourism, work trips, medical treatment, and family visits are all social activities that promote population flows [37]. In terms of spatial carriers, the demands of population flows consist of basic public service facilities, labour and employment facilities, and commercial service facilities. Castells studied "flow space" from a sociological perspective, defining "flow space" as a material organization in which the components interact with each other through "flow" with a temporal component [38]. Our study introduces the concept of flow space to construct a spatial organization model of PL flow, which is based on the spatial flow of the population in the region and addresses the limitations imposed by administrative jurisdiction on the land-use planning quota and planned spatial allocation.

The model fully considers the spatial flow characteristics of geographical factors. Based on the characteristics of the spatial correlation between population flows and land-use demand, the model analyses the spatial demand for land generated by population flows and then conducts spatially differentiated land resource allocation and optimization and analyses the agglomeration and diffusion of the population and land resource factors.

Our study uses the regional population served and the regional migrant population (i.e., those who are residents for less than six months and are counted among the regional population served) obtained from big data on mobile phone signalling to analyse the coupling relationship between the regional migrant population and new urban construction land. Factors such as economic development level, industrial structure, investment drivers, and household registration policies are included in the model as control variables (Table 2) to estimate the influence of population size on urban construction land expansion.

Table 2. Correlation factor analysis model.

Variable Type	Indicator	Explanation
Dependent variable	Scale of urban construction land	The scale of construction land required by the regional migrant population.
Control variable	Economic development	Regional GDP is selected as a measure of economic development. The data were derived from the statistical yearbooks of Nanjing, Luhe District, and Pukou District.
	Industrial structure	Land-use changes in cities with different industrial structures display different characteristics and, in particular, exhibit rapid expansion in cities with a high industrial share. The proportion of the secondary industry (the share of the output value of the secondary industry in GDP), C, is used as a control variable to measure the industrial structure.
	Household registration system	Referencing the differentiated household settlement policy, F is defined as a dummy variable representing the inclusiveness of an urban household registration system, with 1 = strictly controlled (cities with a population of more than 5 million), 2 = reasonably regulated (3–5 million), 3 = reasonably lifted (1–3 million), 4 = appropriately lifted (0.5–1 million), and 5 = completely lifted (less than 0.5 million).
	Migrant population size	The size of the migrant population is obtained by calculating the coefficient of the population served on the basis of the regional resident population. Using big data on mobile phone signalling, the data of the population actually served in NJNA from September to December of 2017 and from October to December of 2019 were collected.

To avoid multicollinearity among multiple variables, a variance inflation factor (VIF) was introduced for testing. A larger VIF indicates a more serious multicollinearity problem, and a rule of thumb is that the problem is not serious if the maximum VIF does not exceed 10. Stata 15.0 software was used to conduct multicollinearity analysis with four control variables, i.e., GDP, proportion of the secondary industry (C), household registration system (F), and population flow (M). Using Stata 15.0 software, the mixed ordinary least-squares (OLS) model, fixed-effects, and random-effects were estimated separately. First, depending on the F test results, the mixed OLS model was used if the p value > 0.05; otherwise, the fixed-effect or random-effect model was used. The Hausman test was performed on fixed effects and random effects, and random effects were used if the test results were significant ($p > 0.05$); otherwise, fixed effects were used.

The "relationships" in the population flow network are quantified to analyse the characteristics and patterns of the overall structure and local nodes. The degree centrality $C_0(S_i)$ in social network analysis is adopted to describe the population flow and is used as the spatial organization model of PL flow for calibration.

$$C_0(S_i) = \sum_{i=1}^{g} S_{ij}(i \neq j) \quad (5)$$

where $C_0(S_i)$ is the degree centrality of node i; $\sum S_{ij}$ is the sum of the numbers of connections between node i and other $g-1$ nodes; and the sum of the values in rows and columns where node i is located is calculated, excluding the connections between node i and itself.

According to the Code for Classification of Urban Land Use and Planning Standards of Development Land (GB50137-2011), land types other than residential land and industrial land are merged into service management land based on the division into production land, support land, and living land, as well as the division into lands for living, production, public service, and ecological functions to achieve a vertical comparison. Considering that the goal of optimizing urban and rural land resource allocation is to continuously improve the degree of coordination of population, economy, and land resource allocation in the region, the degree of comprehensive coordination of PLI coupling, H, is used as an adjustment factor for the spatial organization of the PL flow. Its specific calculation method is described above. The model of the spatial organization of the PL flow is established as follows:

$$Mi = F_i \times A - 1 - Pi \quad (6)$$

$$Li = [(F_i \times A - 1 - Pi] * Hi * \overline{L1'}) + [(F_i \times A - 1 - Pi] * Hi * \overline{L2'}) \cdot \text{*Si} \quad (7)$$

where F_i denotes the size of the population actually served; P_i represents the registered population; M_i is the size of the migrant population; A denotes the coefficient of the population served; $\overline{L1'}$ is the demand of the migrant population for industrial land; $\overline{L2'}$ is the demand of the migrant population for public service management land; $C_0(S_i)$ is the standardized value of the degree centrality of the study unit and is a positive correlation coefficient used to adjust the demand for public service management land; and H_i is the standardized value of the PLI coupling coordination degree of the study unit, with regions with H_i lower than 0.5 being negatively correlated and those with H_i higher than 0.5 being positively correlated. After the standardization of extreme values in the measurement data L_i, spatial characterization and overlay analysis were conducted using GIS software to analyse the layout pattern of the spatial organization of the PL flow.

4. Results

4.1. Analysis of PLI Coupling Coordination Degree

A model for measuring and evaluating the PLI coordination degree was constructed to evaluate the performance of the PL linkage policy at the county level and on a spatial scale, analyse the degree of matching of the immigration of urban populations with the allocation of urban construction land resources and the extent of the development of secondary and tertiary industries, analyse the degree of matching of the emigration of agricultural populations with the allocation of rural construction land resources and the development rate of the primary industry, and then analyse the PL relationship in areas with different urbanization characteristics. This study analysed the regional spatial structure characteristics of NJNA by taking the regional land space as an organic whole for planning and layout and by using the spatial measurement of PL flow. Based on the data of the population actually served and migrant population obtained from big data on mobile phone signalling, spatial overlay analysis was carried out using ArcGIS software, and guidance for the spatial layout optimization of urban construction land was proposed. A planning scenario simulation of the future urbanization of NJNA was conducted to propose future population flow strategies and optimization directions for urban space, agricultural space, and ecological space in Jiangbei under different urbanization levels and different levels of spatial planning to guide the optimal allocation of urban and rural land.

Using the aforementioned PLI coupling degree model for rapid urbanization and agglomeration areas, the current population, land, and economic data after standardization for 2018 were used to analyse the PL coupling degree for the area administered directly by NJNA (Table 3). According to the calculated index values, the PLI of the rapid urbanization area of NJNA has a coupling degree of 0.7085, a comprehensive evaluation index of 0.5807 for the coupling coordination degree, which is in the moderate range. The PLI of the spatial agglomeration area of agricultural development in NJNA (formerly Liuhe District) has a coupling degree of 0.8221, a coupling coordination degree of 0.1284, and a comprehensive evaluation index of 0.3248 for the coupling coordination degree, which is in the low range, indicating the need for further improvement. Overall, the comprehensive evaluation index of the PLI coupling coordination degree of NJNA is 0.5019, which is in the low-to-moderate range for the degree of coupling coordination, indicating that NJNA is in the running-in stage.

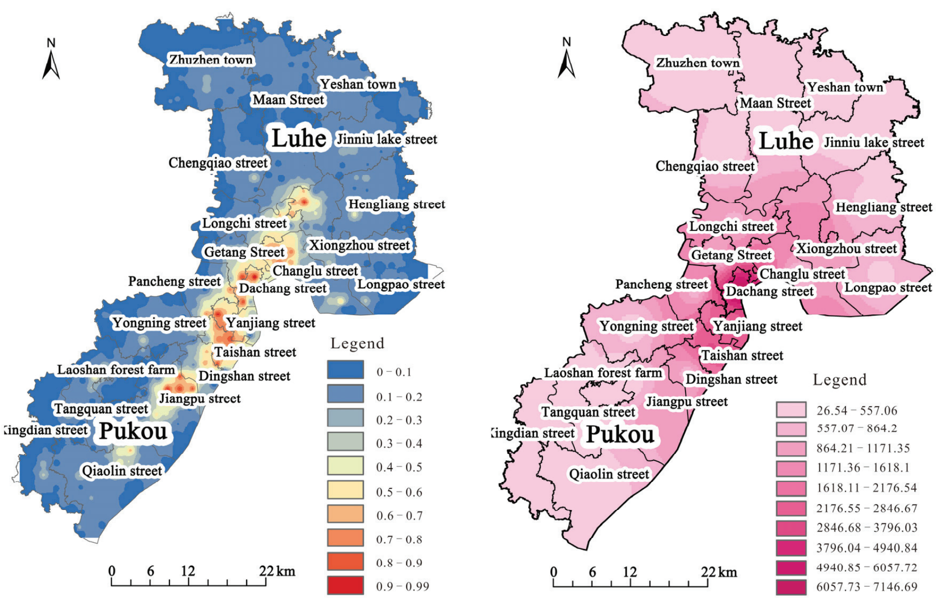
Table 3. Coupling coordination degree of PLI in NJNA.

Classification	Indicator	Value
Rapid urbanization area	Population urbanization rate (Ui)	0.6088
	Land urbanization rate (Li)	0.1050
	Nonagricultural industry development rate (Di)	0.9518
	Comprehensive evaluation index (T_1)	0.4759
	Coupling coordination degree (H_1)	0.5807
Agricultural development spatial agglomeration area	Rural population emigration rate (Ni)	−0.1037
	Reduction rate of rural construction land (Ji)	−0.0527
	Primary industry development rate (Fi)	0.1113
	Rural income growth rate (Si)	0.2959
	Coupling coordination degree (T_2)	0.1284
	Coupling coordination degree (H_2)	0.3248
Degree of comprehensive coordination	Population urbanization rate (Ui)	0.5071
	Land urbanization rate (Li)	0.0090
	Nonagricultural industry development rate (Di)	0.7321
	Comprehensive evaluation index (T)	0.3908
	Coupling coordination degree (H)	0.5019

Currently, urban–rural development is in the urban–rural population transition and accelerated urbanization stage. In the future, a large rural population will move into cities and towns, and agricultural production will remain the basic support industry in this region. As the economic development of NJNA enters the postindustrial stage, the area under direct administration by NJNA will mainly undergo industrial restructuring, transformation, and upgrading, and the population and employment structure will also evolve. The population and employment will be concentrated in the commercial and service sectors of the tertiary industry, and the intensity of the correlation of population and land with secondary and tertiary industries will gradually increase, further enhancing the coupling coordination degree. According to the Lewis theory, when the income of urban residents and the disposable income of rural residents become closer, the effect of differences in urban–rural economic and social factors will gradually balance, and the degree of coupling coordination between population, land, and industrial nonagriculturalization will gradually balance and remain stable. Overall, before 2010, the growth rate of land urbanization in NJNA was generally higher than that of population urbanization, especially in Pukou, where large-scale urban construction and land-use expansion were more prominent. Although this problem has gradually decreased in the past few years, the gap between the quantity and quality of population urbanization still requires continuous attention and coordination.

4.2. Spatial Distribution Characteristics of PL Flow

Through the study of the distribution characteristics of the actual population served based on the cell phone signal data, the relationship among the actual population served, the resident population, and the mobile population is analysed. At the same time, the spatial layout pattern and characteristics of the spatial organization of PL flow in NJNA are analysed by combining the data of the land-use status change survey, as well as the population density, service population, and construction land distribution, to guide the optimization of urban and rural land space (Figure 3). The population density is characterized by a circular distribution with Dachang, Yanjiang, and Taishan subdistricts as the core, gradually decreasing towards the periphery. The population actually served in NJNA is characterized by a circular distribution with Xiongzhou, Dachang, Taishan, and Jiangpu subdistricts as the core, gradually decreasing towards the periphery. The spatial density of construction land is clearly characterized by a band-like core distribution along the Yangtze River, with high-value areas mainly distributed in areas such as Jiangpu, Taishan, Yanjiang, Dachang, and Changlu subdistricts. Overall, Jiangpu, Taishan, Yanjiang, and Dachang subdistricts have greater development potential in terms of population concentration and construction land layout. The core area of Pukou has a more concentrated population distribution and a higher proportion of land for residential and business services. The area around Dacang Street is more concentrated in industrial development, with a high proportion of traditional industrial land. The area around Xiongzhou Street is the regional centre of Luhe District and is a future base for the development of new industries.



a. Spatial density of construction land b. Spatial measurement of PL

Figure 3. *Cont.*

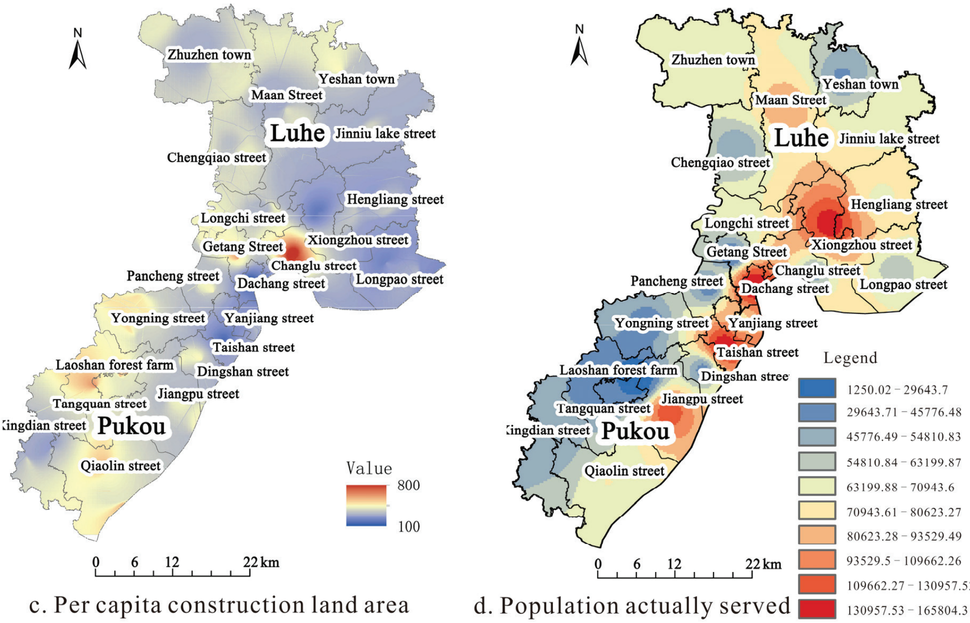


Figure 3. Spatial analysis of PL flow in NJNA.

4.3. Guidance for the Spatial Optimization of Planning

Based on the spatial layout of PL flow in NJNA and the current industrial development characteristics, the spatial planning is optimized to guide the future population aggregation areas in NJNA (Figure 4).

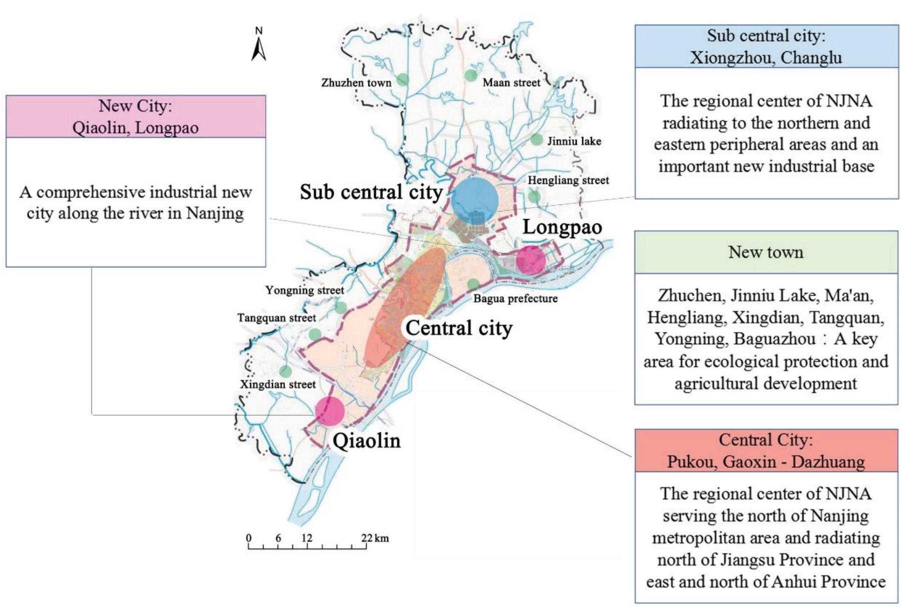


Figure 4. Guidance for the spatial optimization of planning for NJNA.

Optimizing the supply of regional land resources. First, the planned space of urban construction land should be increased in Jiangpu and Taishan subdistricts, which have high population concentrations and are undergoing a rapid increase in the urban immigrant population, and the allocation of planned new land-use quotas should be increased. Second, in the subdistricts of Changlu, Getang, and Yanjiang, the reclamation of rural construction land should be increased, the space of planned urban construction land should be moderately increased, and the allocation of quotas with an increase–decrease linkage should be increased. Third, on the basis of the thresholds for the amount of arable land and the total scale of construction land and without involving permanent basic farmland, the agricultural spatial layout of the subdistricts of Pancheng, Jiangpu, and Taishan should be moderately adjusted, and agricultural land space in the subdistricts of Dingshan and Changlu should be increased.

Reconfiguring the spatial pattern of town development. The layout of the town hierarchy of "central city-sub central city-new city-new town" is planned. Among these components, the central city is composed of two groups, Pukou and Gaoxin-Daicang, and is the regional centre of NJNA, serving the northern part of the Nanjing metropolitan area and radiating north of Jiangsu and east and north of Anhui. It is necessary to combine the industrial development function with the living function to improve the population distribution, industrial carrying capacity, and urban service level. The subcentral city consists of the Xiongzhou group and the Changlu industrial sector, which is the regional centre of NJNA radiating to the northern and eastern peripheral areas and an important new industrial base, and needs to strengthen the linkages with the main urban area of Nanjing, the central town, and the surrounding villages to promote the integrated development of urban and rural areas. The new city, including Qiaolin New City and Longbao New City, is an industrial new city along the river in Nanjing, which needs to promote the integrated development of industry and the city and provide talent, land, and industrial support for the development of the new city. The new towns, including Zhuchen, Jinniu Lake, Ma'an, Hengliang, Xingdian, Tangquan, Yongning, and Baguazhou, are key areas for ecological protection and agricultural development and need to highlight ecologically oriented economic development and strive to become idyllic towns with their own characteristics.

5. Discussion

5.1. Analysis of the Influence of the Migrant Population on Construction Land

This study used mobile-phone-signal-based population flow data obtained from the NJNA Big Data Centre and the Urbanization and Urban—Rural Planning Research Centre of Jiangsu. Data on the population actually served within NJNA were used to obtain the migrant population data on the population served. The sample data were statistical data for three months in both 2017 and 2019. Using Stata 15.0, estimation was carried out with the mixed OLS model, as well as fixed-effects and random-effects models, on the population data obtained at each base station in NJNA (Table 4). The p value was less than 0.05 according to the F test; therefore, the mixed OLS model was not adopted. Regarding the Hausman test, only the p value of the total scale effect of population on construction land was less than 0.05; therefore, the fixed-effects model was used for construction land, while random-effects analysis was conducted for both industrial land and public management and service land. Overall, the R^2 and F tests were significant, and the model estimation results had a high explanatory power. There was a large difference in the demand of the migrant population for various types of urban land; therefore, the significance of the model estimation results varied widely. The migrant population had a positive impact on the total scale of construction land; however, the impact was not statistically significant, indicating that an increase in the migrant population did not necessarily increase the total scale of construction land. The nonpermanent population had a positive impact on construction land, but the significance varied greatly across different types of urban land. The increase in the migrant population had a positive impact on the expansion of industrial land and passed the 1% significance level test, probably because the short-term population for business and economic exchange influenced the expansion of industrial land. Management and service land in large cities hosts quality public services, such as culture, education, medical care, tourism, and commerce; hence, the increase in the migrant population had the largest (0.182) elasticity coefficient, which was statistically significant, for the expansion of land for public management and services.

Table 4. Full-sample estimation results for the impact of the migrant population on construction land.

Variable	Construction Land		Industrial Land		Public Management and Service Land	
	FE	RE	FE	RE	FE	RE
Migrant population	0.387	0.321 **	0.143 ***	0.178 ***	0.182 ***	0.530 ***
GDP	0.979 ***	1.33 ***	0.221 **	0.393 ***	0.767 ***	0.998 ***
Proportion of secondary industry	−0.336 ***	−0.368 ***	−0.0726 *	−0.0669 *	−0.203 ***	−0.233 ***
Household registration system	−18.60 ***	−21.12 ***	−2.741 ***	−2.429 ***	−6.985 ***	−7.025 ***
Constant	188.8 ***	145.7 ***	37.73 ***	19.96 ***	73.71 ***	51.93 ***
R^2	0.3011	0.7351	0.3206	0.6048	0.5549	0.7752
F test/chi-square test	5.33	92.17	4.50	62.55	4.35	143.35
Hausman test	Prob > chi^2 = 0.0000		Prob > chi^2 = 0.0195		Prob > chi^2 = 0.1642	

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; FE and RE denote fixed effects and random effects, respectively.

5.2. Regional Development Orientation under Spatial Optimization

The vision for the long-term development of NJNA is to build a high-standard national new area. Thus, it is necessary to reserve sufficient space for development to ensure that the space is sufficient to support the gradual transition from a "subcentral city" and "regional centre" to a "national new area". When determining the urban growth boundary, it is important to account for the fact that the population concentration area evolves continuously. As NJNA focuses on high-end and diversified industrial development in the future, it is still necessary to retain some traditional industries with a sound development base and a certain employment density to lower the barrier to urbanization among the local rural population and provide a motivation for population concentration and livelihood improvement. Key cities and towns have become agglomeration areas for adjusting the industrial structure of townships. Townships with concentrated industrial areas with a population of more than 50,000 will gradually develop into key cities and towns. At the stage of industrial structure development, townships need to make use of industrial development to meet local employment demand and control the speed of nonagricultural construction. The spatial layout of urban and rural land will form an "organic + clustered" development model, and life service centres will have diversified cores to meet the needs for transportation, service, and leisure industries and to improve the overall quality of life and radiating capacity of NJNA. Relying on the Pukou–Xiongzhou central city belt and organizing out and strengthening the fast-track economic development axis that radiates to the rural areas in the east and west should be areas of focus to promote the extension of quality urban resources to small towns and rural areas. A public service facility system at the "district level–subdistrict and community level–grassroots community level" is formed in urban areas, and a public service facility system at the "town level–rural community level" is formed in rural areas. The town level and rural community level in rural areas are comparable in scale to the urban residential district level and grassroots community level in urban areas, respectively.

5.3. Synthesis of Research Methods

In the context of rapid global urbanization, it is important to enhance the efficiency of land resource utilization through land-use optimization for regional sustainable development. At present, there are several studies on the optimal allocation of land resources, and most scholars have conducted comparative studies on land resource optimization from different perspectives and using different methods. In general, on the one hand, there are an increasing number of studies applying big data methods, including cell phone signal data, metro bus swipe card data, population migration flow data, and urban commuting data. For example, Liu et al. [39] constructed an intracity employment mobility network based on interregional employment mobility data decoded from cell phone signal data in Wuhan and studied the characteristics of intracity employment mobility, which found that intracity employment mobility in Wuhan was unevenly distributed in terms of quantity, and a large amount of employment mobility was concentrated among a few streets, which further gave suggestions for adjusting urban planning. On the other hand, the optimization of land resources is considered from a multifunctional perspective. For example, Sheikh et al. [40] combined multiobjective optimization and multicriteria decision models for land-use optimization to present an efficient methodology for land-use optimization based on the minimization of runoff and sediment and the maximization of economic benefits, occupational opportunities, and land-use suitability in the Tilabad watershed in northeastern Iran. Liao et al. [3] comprehensively considered three types of land functions—production, living, and ecology—and used a multiscale land-use optimization method to optimally simulate the quantitative structure and spatial distribution of land use, providing scientific support for the sustainable use of rural land resources in China. Our contribution lies in combining multifunctional scales with big data methods, introducing the concept of flow space, and combining the regional service population identified by cell phone signal data to optimize the land resource allocation analysis. This approach more carefully considers the impact of population flow on regional development and the characteristics of demand for land resources, is applicable to the study of land resource optimization in most regional development zones, and involves simple methods, accurate data, and adaptability. In addition, this method is applicable to the study of land resource optimization in most regional development zones.

5.4. Highlights and Limitations

First, this study is based on the spatial mobility characteristics of the population in the region and overcomes the limitation of administrative divisions on land-use planning indicators and spatial allocation planning. Second, the study analyses the spatial demand for land generated by population flow by combining the flow of geographical factors with the correlation characteristics of population. This approach clarifies the spatial allocation of population and land resource elements by constructing a “people–land” flow spatial organization model, which makes the allocation of land resources more in line with the actual demand. The study has certain implications for expanding the theoretical knowledge and methodological ideas on the optimal allocation of urban and rural land resources with the development of new urbanization.

Because the research topic involves a variety of socioeconomic development factors, this study has some limitations. First, on the basis of the construction and implementation of a land spatial planning system, we have explored theoretical paths and simulated planning scenarios in combination with the PL linkage policy and have proposed guidance for the spatial optimization of planning; however, we did not carry out an empirical analysis combined with specific planning cases, which should be conducted in the future. Second, the research results could be made more universal and better applied in practice by obtaining more accurate and real-time multisample data of regional population flows and migration to inform the layout of industrial development and by integrating satellite remote sensing data with socioeconomic factors.

6. Conclusions

Coordinating the regional PL relationship is an important topic in urbanization. By investigating the coordinated development relationship between population urbanization and land urbanization, this study explores the optimal allocation of urban and rural land resources in rapidly urbanizing areas and identifies the synergy between the spatial allocation of resource factors and the flow of population factors. This study provides new ideas for addressing the PL conflict and coordinating the PL relationship and provides important basic support for the implementation of land spatial planning, as well as the management and control of land use.

(1) From the perspective of the comprehensive evaluation of the PLI coupling coordination degree, the overall NJNA has a low-to-moderate degree of coupling coordination and is in the running-in stage. Before 2010, the growth rate of land urbanization in NJNA was generally higher than that of population urbanization, especially in Pukou, where large-scale urban construction and land-use expansion were more prominent. Although this problem has gradually decreased in the past few years, the gap between the quantity and quality of population urbanization still requires continuous attention and coordination. Overall, the Jiangpu, Taishan, Yanjiang, and Dachang subdistricts have greater development potential in terms of population concentration and construction land layout.
(2) Based on the analysis of the spatial layout of the PL flow, the spatial optimization of the future population concentration area of NJNA is proposed. First, the planned space of urban construction land should be increased in the Jiangpu and Taishan subdistricts, which have high population concentrations and rapid increases in urban immigrant populations, and the allocation of planned new land-use quotas should be increased. Second, in the subdistricts of Changlu, Getang, and Yanjiang, the reclamation of rural construction land should be increased, the space of planned urban construction land should be moderately increased, and the allocation of quotas with an increase–decrease linkage should be increased. Third, on the basis of the thresholds for the amount of arable land and the total scale of construction land and without involving permanent basic farmland, the agricultural spatial layout of the subdistricts of Pancheng, Jiangpu, and Taishan should be moderately adjusted, and agricultural land in the subdistricts of Dingshan and Changlu should be increased.
(3) This study can also provide a reference for the optimal management of land resources in similar areas at home and abroad. First, it is necessary to strictly control the occupation of ecological and agricultural space resources by economic development and avoid inefficient development of urban space. At the same time, it is necessary to guide the allocation of various factors and resources to match the change in regional population scale and to solve the problem of "big city disease" caused by the excessive concentration of population and the problem of "hollow villages" caused by excessive population loss. Second, it is necessary to leverage urban and rural land stock resources into development advantages, shift from reliance on new construction land indexes to stock land redevelopment, and formulate new strategies for stock land utilization based on population size. Finally, it is necessary to fully consider the problem of imbalance between the increase in land scale and population in urban and rural areas and to promote the unified deployment of urban and rural construction land through information exchange and resource conversion to improve the efficiency of construction land utilization.

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Evaluation of the Spatial Effect of Network Resilience in the Yangtze River Delta: An Integrated Framework for Regional Collaboration and Governance under Disruption

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Abstract: Public health emergencies are characterized by significant uncertainty and robust transmission, both of which will be exacerbated by population mobility, threatening urban security. Enhancing regional resilience in view of these risks is critical to the preservation of human lives and the stability of socio-economic development. Network resilience (NR) is widely accepted as a strategy for reducing the risk of vulnerability and maintaining regional sustainability. However, past assessments of it have not sufficiently focused on its spatial effect and have overlooked both its internal evolution characteristics and external threats which may affect its function and effectiveness. Therefore, we used the Yangtze River Delta Region (YRDR) as a case study and conceptualized an integrated framework to evaluate the spatial pattern and mechanisms of NR under the superposition of the COVID-19 pandemiv and major holidays. The results indicated that the topology of a population mobility network has a significant effect on its resilience. Accordingly, the network topology indexes differed from period to period, which resulted in a decrease of 17.7% in NR. For network structure, the Shanghai-Nanjing and Shanghai-Hangzhou development axes were dependent, and the network was redundant. In the scenario where 20% of the cities were disrupted, the NR was the largest. Furthermore, the failure of dominant nodes and the emergence of vulnerable nodes were key factors that undermined the network's resilience. For network processes, NR has spatial effects when it is evolute and there is mutual inhibition between neighboring cities. The main factors driving changes in resilience were found to be GDP, urbanization rate, labor, and transportation infrastructure. Therefore, we propose a trans-scale collaborative spatial governance system covering "region-metropolitan-city" which can evaluate the uncertain disturbances caused by the network cascade effect and provide insights into the sustainable development of cities and regions.

Keywords: network resilience; interrupt simulation; spatial effect; regional governance; Yangtze River Delta region

1. Introduction

Network resilience refers to the ability to withstand shocks and to restore, maintain, or improve the characteristics and critical functions of a system, as well as providing an important supporting role to each unit within a region [1,2]. As COVID-19 continues to spread throughout the world, it is having a significant impact on economic and social development [3,4]. Since it is extremely transmissible, restricting the mobility of the population has allowed the spread of the disease to be effectively contained while also reducing urban connectivity [5,6]. The "blocking cities" measures have reduced external risks [7]. Meanwhile, the incident has had an adverse effect on regional connections as well as routine operations [8]. The global spread of COVID-19 was an unconventional disaster. As such, it may be hypothesized that urbanization will increase vulnerability [9]. When not supported by a healthy and safe environment, such an event can even produce long-term "shock" and "aftereffects" within a short period of time [10]. With innovations in risk management, such as dynamic adaptation, comprehensive promotion, and multi-stakeholder collaboration, urban resilience is becoming a hot topic in disaster prevention, risk mitigation, and urban planning. To promote better regional sustainable development, it may be beneficial to make cities more resilient to shocks.

As urbanization is characterized by high density and mobility, it has broken through static administrative boundaries [11]. The mobility of the population has come to be characterized by scale, normality, dynamism, and, most importantly, a complexity of behaviors [12]. There has been a precipitous increase in transmission speed, resulting in an increased risk of security incidents. Therefore, it is important to explore population mobility using the theory of mobility space and from a network perspective in order to assess the regularity of spatial movement at a city or regional scale, as well as the dynamic characteristics of inter-city spatial connections. Urban network resilience can be used to evaluate regional resilience, which refers to the ability to maintain, improve, or restore the original performance and function following a shock [13]. Research in this field can be put into one of the following categories: concept and connotation, assessment of network structures, and simulations of shock resistance. Urban network systems can resist the impacts of acute external shocks while also adapting to internal pressures by improving the strength and agility of social, economic, ecological, engineering, and organizational relationships [14,15].

Much empirical research has been conducted on global and regional networks from the perspectives of enterprise location, information networks, and traffic connections. A great deal of literature has been produced about population mobility, especially the characteristics of intercity travel during specific periods, such as May Day, National Day, and the Spring Festival [16–19]. Network analysis has become the main method by which to study population mobility, and it has become a paradigm of how networks are represented. Moreover, the COVID-19 pandemic has led to more and more attention being paid to network resilience [20,21]. Frequent natural disasters and manufacturing emergencies can interrupt a network and affect the regular operation of the cities, with unpredictable consequences [22]. Generally, the investigation of targeted and random attacks on city nodes determines the degree of attenuation, the influencing factors, and the effectiveness of various optimization strategies for a specific network structure [23]. As a result, many cities are at risk of disasters or attacks, resulting in disruptions in urban communication. Thus, scenario simulations of networks under disruption can help predict whether urban networks will be able to resist potential risk to their operational capacity and capabilities when a public health emergency occurs.

However, there are also some research gaps in the previous literature, such as the absence of theoretical exploration. Although empirical studies have been important in understanding the characteristics and causes of population mobility, there has not been a unified paradigm of research due to the lack of systematic theoretical studies. Most studies have focused on economic development or disaster prevention and mitigation, while only a few have considered spatial relationships and effects. Urban network resilience should be given enough spatial consideration, which is different from the aforementioned regional resilience. additionally, we should focus on how to discuss the mechanisms of urban network resilience in sufficient depth, rather than building a network and analyzing its characteristics. Network science offers new perspectives on the complex networks in social, economic, and technological systems [24]. Network robustness and resilience are critical to the reduction of risk and mitigation of damage. Essentially, network resilience is the ability of a system to maintain its essential functions when it faces internal disturbances or external changes [25]. Complex networks function as a result of the robustness of their structures, which can maintain connectivity if some nodes or edges are removed. Cities and regions are complex coupled systems which are characterized by complexity, diversity, nonlinearity, uncertainty, and multiscale nesting. Evaluations of network resilience offer an analytical perspective between humans and complex systems that are continually adapting [26].

Thus, we propose an integrated approach which utilizes both complex systems and spatial modeling analysis to identify the effects of a public health emergency disruption on regional network resilience. A multi-perspective network based on big data will help to understand spatial patterns and resilience under disturbance. The aims of our study are to: (1) conceptualize network resilience from the perspectives of a complex adaptive system (CAS) and a complex network (CN); (2) evaluate network resilience and its characteristics under different disruption scenarios; and (3) identify dominant and vulnerable nodes in urban linkage networks. Such efforts may answer the following scientific questions: What are the concepts, connotations, and characteristics of network resilience in the context of CAS and CN? What are the characteristics of population mobility network linkages over time? What are the main factors that affect network resilience under disruption due to external shocks? How can we reshape regional spatial structures for sustainable regional development while improving network resilience? We believe that the results of our study will provide new insights for policymakers when it comes to considering regional collaboration and identifying a trans-regional system of coordinated governance.

2. Conceptual Framework of Network Resilience from CAS

2.1. CAS Theory and Its Characteristics

CAS theory was developed by the Santa Fe Institute in the United States in the 1980s. It focuses on interactions between individuals and the environment, and thus represents a new means by which to view systems. There is an argument that the complexity of a system is caused by an individual's ability to adapt. The system in question will exhibit adaptive behavior in response to external disturbances. Diverse heterogeneous individuals also interact in autonomous and diverse ways which affect both their evolutionary paths and the structure of the system [27]. According to the theory, the transformation, evolution, and development of an organization are collective outcomes of the subject's active knowledge of the outside environment. There is a critical element of adaptive creation complexity, and one of its most important elements is adaptive subjectivity [28]. System evolution is fundamentally affected by the constant interactions between adaptive systems and their environments. Through the interaction process, the adaptive issue is raised to a new level, exhibiting a more complex structure and behavior [29].

2.2. Complex Network Resilience from CAS

Several articles have introduced assessment methods for resilience based on CAS, which authors have argued facilitate a better comprehension of the structure and operation mechanisms of an urban system [30,31]. The use of CAS theory to explore how CNs become resilient has not been reported in the literature. Thus, we define urban network resilience first as the dynamic nature of the structural characteristics of a network, as well as the internal adaptive adjustment process when the regional space system experiences external shocks (Figure 1). Complexity lies at the core of diversity, and the complexities associated with network resilience are derived both from the diversity of internal linkages and from the active adaptation of internal elements. Essentially, it consists of the interconnections among network nodes and the continuous adaptation of the system to external disturbances.

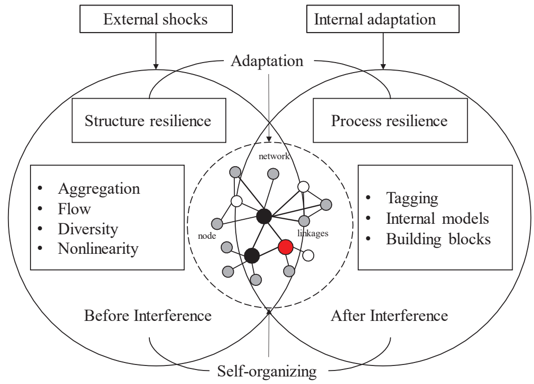


Figure 1. Conceptual framework for regional network resilience based on CAS.

When the resilience of a certain regional network is diminished, the function of the entire regional system will be affected. As a result, a previously stable structure and the ability to adapt to shocks and impacts will be altered, which will affect the entire regional network system. Due to structural changes, the existing structure will not have enough resistance and adaptability, and therefore, its resilience will be weakened in response to external shocks. In one sense, such a change would improve the overall network resilience (i.e., by reducing the redundancy of the offset network). On the other hand, such a change would weaken the resilience of the existing structure due to structural changes. Therefore, simulations of disruptions to urban networks can assist in predicting the capacity of regional urban networks to withstand potential risks, thus helping to reduce the adverse impact of disasters and improve regional resilience strategies.

According to our theoretical concepts, a complex network system is composed of two fundamental attributes: structure and process. These notions are different but interrelated. When a network system is subjected to external shocks, the first thing to occur is a change to its structural characteristics, i.e., the preparatory stages before the interruption. As a result, the system will experience self-regulation and adaptation, which is known as process resilience. This represents the adaptability and resilience of the system. Normally, when an external entity attacks a network node, the nodes and linkages suffer the first consequences. These network topology characteristics indicate the degree of impact of the node. After a period of self-recovery, the systems recover or approach their original state via self-regulation. Therefore, simulations of the topological indexes of network resilience, before and after an interruption, can reflect both the structural and process characteristics of the network to reveal the system resilience.

2.3. Characteristics and Mechanisms of Complex Network Resilience

CNs are used to analyze changes in network characteristics, while CASs are used to provide a qualitative understanding of the adaptation process of a system globally. Combined with the seven main attributes of CAS theory, the basic elements of the complex adaptive system are summarized below, and the characteristics of complex networks are deduced.

Aggregation, Flow, Diversity, and Nonlinearity are four basic features in CASs; they correspond to Centrality, Density, Diversity, and Aggregation in CNs, reflecting the structural characteristics of network resilience. The term "structural resilience" refers to the resilience problem caused by the topology of a network, with a particular focus on the physical and logical connections between network nodes, including the resilience of the nodes themselves, the resilience of the connections, and the overall resilience of the network. On the one hand, node and connection resilience emphasizes the destructive ability of these entities, while on the other, overall toughness emphasizes the ability of a network to self-organize and coordinate itself, as well as to coordinate among its dimensions. The specific correspondence is as follows:

- Aggregation indicates that simpler subjects can emerge with more complex behavior through interactions among aggregates. The interactions between these subjects can give rise to higher-level subjects that generate new meta-agents through re-aggregation. This forms the hierarchy of a CAS. Using complex network centrality as a metric, it is possible to determine the hierarchy of a network of cities, which enables an urban network to accommodate a hierarchy of nodes. Generally, cities with high centrality in a network are highly distinguished, core components which enhance the cohesiveness and competitiveness of the network, but also increase the vulnerability of the network structure, since non-core cities are highly dependent on core cities.
- Flow refers to the continuous flow of resources between subjects or between the subject and the environment, including the flow of information, logistics, and capital. The nature of the flow will directly impact the evolution of the system. Network density is an important indicator that precisely reflects the complexity of the overall network. A higher density of nodes will result in a greater number of interconnections and a greater degree of mobility.
- Diversity results from the continuous adaptation of a subject; each new adaptation creates new possibilities for further interactions. Through a continuous cyclical process, significant differences between subjects occur, which contributes to the diversity of the system. This is one of the most important features of a CAS. Whenever the elements of a complex network are adversely affected by external factors, such as shocks, attacks, etc., in the process of communication through a particular path, the normal operation of the network can be maintained by quickly choosing other paths of communication.
- Nonlinearity is characterized by the idea that the whole is greater than the sum of the parts. Interactions between individuals are not simple causal relationships, but complex relationships based on mutual feedback within an adaptation process. Thus, CASs exhibit a wide range of properties and states, and nonlinearity is an inherent source of complexity. In complex networks, nonlinearity is represented by the average aggregation coefficient i.e., the degree of aggregation between neighboring nodes. Consequently, the process of aggregation also changes in nonlinear growth as a result of aggregation in the network, resulting in a complex relationship comprising mutual feedback among nodes.

Tagging, building blocks, and internal models are all reflections of evolutionary mechanisms in CASs; when applied to the interpretation of CNs, they can be characterized as internal processes of recovery and challenges to a regional network following an external shock. This aspect of network resilience is more process-oriented, in contrast to the structure and function that directly reflect the state at a given moment. How to interpret the true resilience of a network system requires a process of system adaptation and recovery. Thus, these three mechanisms can be used to analyze the resilience of a system in terms of its ability to withstand risk and recovering more effectively.

- Tagging is the process of aggregation formation, tagging facilitates the identification and selection of different subjects or targets and selective interactions. The network size, i.e., the number of nodes and connections, is used to describe the corresponding network characteristics, which can provide a good explanation of the selection behavior of subjects when networks are aggregated.
- Building blocks are the main feature of the internal mechanism, i.e., they are closely related to diversity, which generates complexity due to the diverse combinations which exist within a CAS. The combination of blocks will be changed by an agent in response to new circumstances. Using connectivity to represent the building blocks of a network system reveals that networks are composed of interconnected combinations of internal nodes and nodes; and the greater the connectivity, the greater the diversity, i.e., the more complex the internal mechanism.

- Internal models represent the internal structure of a subject through which the environment and behavior of that subject can be inferred. The subject relies on its complex, unique internal structure and can accumulate experience and learn or predict certain things to demonstrate that each subject in the system has its own complex internal mechanisms. The ability to diffuse factor flows in urban networks is portrayed using transmissibility, which is related to the shortest path between nodes. Higher transmissibility means that the urban nodes in a network can achieve faster exchanges of factors such as information, knowledge, and capital, which promotes inter-city learning and innovation and enhances the resistance of a region to crises. In response to shocks, paths with fewer hops are more reliable, and at the same time, can respond to external changes more rapidly and cope with disruptions more smoothly. Quantitative assessments of network transportability using the metric of network efficiency are directly based on the transport functions achieved by the network. They can also better portray the internal mechanisms of complex networks.

3. Materials and Methods

A technical diagram was derived based on the concept and mechanism of urban network resilience, consisting of three main steps. The first step is to build the population mobility network. We constructed the network in different periods using Baidu migration data, which describes the characteristics of the general network. In the next step, seven network typological indicators were selected to measure the NR. The third step involved exploring the attribution of NR. A spatial econometric model was used to analyze the factors contributing to NR and reveal its evolution processes (Figure 2). Furthermore, dominant and vulnerable nodes could be identified to enhance the regional network structure and improve the sustainability of the integrated area.

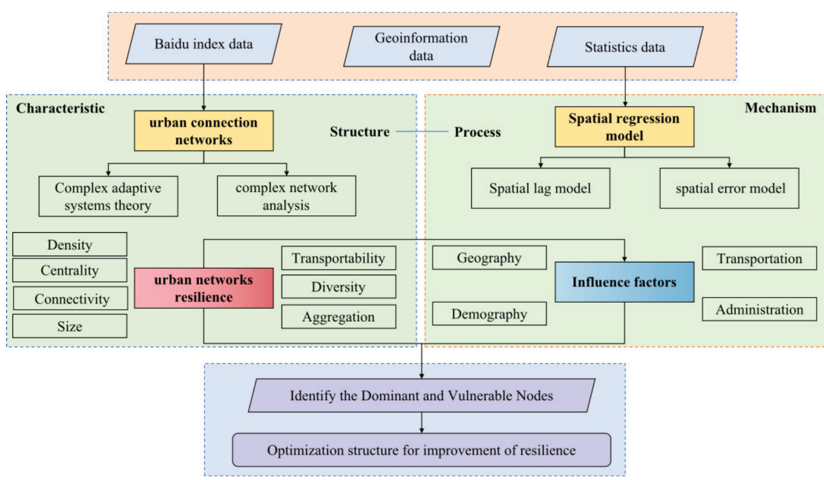


Figure 2. Integrated framework of network resilience for population mobility.

3.1. Study Area

The Yangtze River Delta region (YRDR) is located in the east of China (Figure 3). It is one of the largest urban agglomerations in the world, comprised of Jiangsu, Zhejiang, and Anhui provinces, as well as the Shanghai municipal government. With a population of 0.227 billion people in 2019 and an area of 358,000 square kilometers, this region accounts for 3.69% of China's total land area. Approximately 1/6 of China's population lives in this area, and nearly 1/4 of the national economic output is derived from it. It is one of the most densely populated and economically developed areas in the country. The urbanization rate in this region reached nearly 75% in 2020.

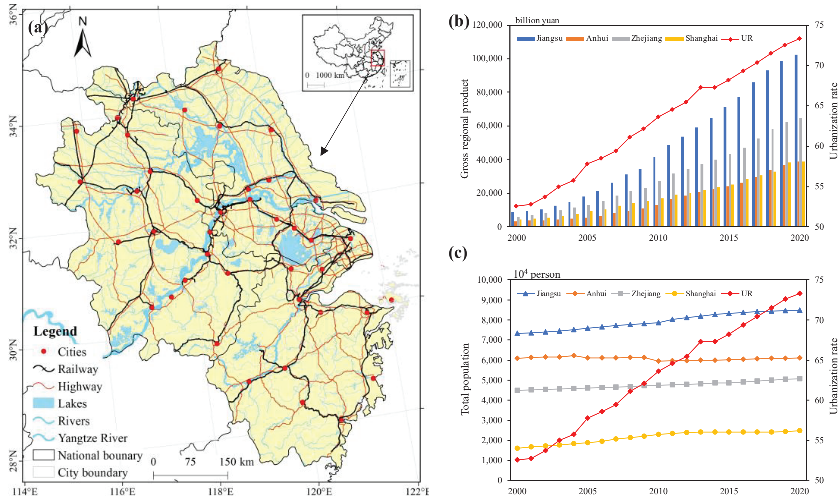


Figure 3. The Yangtze River Delta region. (**a**) The study area; (**b**) Population and urban ratio change from 2000 to 2020; (**c**) GDP and urban ratio change from 2000 to 2020.

With the most active economic development, the highest degree of opening to the world, and the most substantial innovation ability, YRDR plays an essential strategic role in national modernization in China. Since 1983, it has been exploring how to break down administrative boundaries and promote intercity cooperation. Yangtze River Delta integrated development has been promoted as a national strategy, promulgating the policy of "Outline of the Regional Integration Development Plan of the Yangtze River Delta" since 2019. This had made the region a focal point for socio-economic development and has considerably increased the rate of urbanization. As the most integrated region in China, the YRDR has apparent variations among the different scales. There has been a rapid flow of population, technology, capital, transportation, and tourism, resulting in the formation of a polycentric and flat network space [32,33]. However, due to the impact of COVID-19, inter-city mobility has declined significantly, and some connections have been "weakened" or even "interrupted". The urban network structure has also been significantly impacted by these disruptions.

3.2. Data Sources

(1) Population mobility data. These data come from the Baidu Migration Dataset, provided by the Baidu Huiyan platform (https://huiyan.baidu.com/products/platform, accessed on 20 January 2022), which records the intensity of population mobility between any two cities and visualizes movement during a specific period [34]. Although it cannot capture all the migratory population based on the availability of smartphones, when using big data to analyze the spatial characteristics of population mobility, dimensionless measures and relative indicators of the data are better than those reflected by absolute values [35]. We collected the daily population mobility data of 41 cites in the YRDR from 19 January to 27 March 2021 and defined a differential ratio indicator to compare the incoming and outgoing population using the following equation:

$$r = \left(\sum_{city=i}^{N} \left| \frac{in_{numcity}}{out_{numcity}} - 1 \right| \right) / N \tag{1}$$

where $in_{numcity}$ and $out_{numcity}$ are a city's incoming and outgoing populations and N is the number of cities. Generally, the ratio of $in_{numcity}$ to $out_{numcity}$ should be near 1, and r

should be near 0. Whenever incoming and outgoing flows of cities are not balanced, *r* is significantly higher than 0.

According to the "The General Office of the State Council on the arrangement of holidays in 2021", the Spring Festival holiday took place from 11–17 February, a total of 7 days, in 2021. As the travel period, we selected days when the daily passenger flow was higher than the average and the difference was greater than the average. Spring Festival transport data can be divided into three periods (Figure 4). The first concerns the return period (3–10 February), when most people return to their hometowns for family reunions. From 11–17 February, the Spring Festival period, the inter-city population fluctuated to some extent. The second is the leaving period (from 18–28 February), when people leave their hometowns to return to the city where they currently live. The "ordinary" period from 12–24 March was selected for comparison. Due to the impact of the resurgence of COVID 19 across the country before 2021, the total mobility before the Spring Festival was significantly less than what was observed subsequently; this was mainly related to the local policy proposed at that time. Therefore, it was appropriate that we chose this period to analyze the characteristic of population mobility under a disruption simulation. The data we used were the sum of daily population movements in each city during the three phases mentioned above, which illustrated trends in inter-city movements during this time frame.

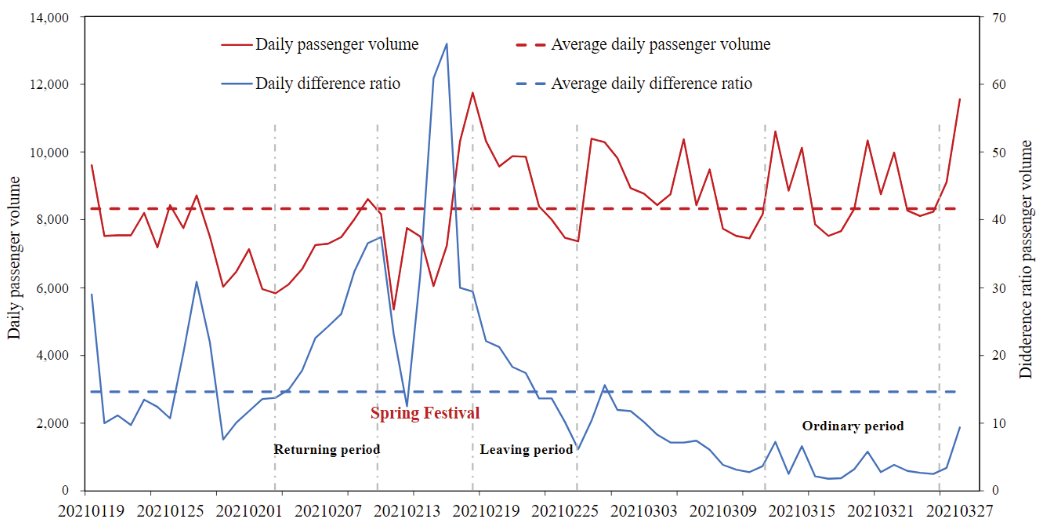


Figure 4. Passenger volume from January to March during the Spring Festival in 2021.

(2) Social statistical data. Socio-economic statistics and the transportation and tourism data of each city, including GDP, per capita GDP, every year resident population, tertiary industry share data, employment data, and road mileage data of each city, were obtained from the provincial and municipal statistical yearbooks and statistical bulletins in 2021.

(3) Geographic Information Data. The administrative district boundaries and city administrative centers were obtained from the National Basic Geographic Information Center database at a resolution of 1:4 million (https://www.resdc.cn/, accessed on 22 February 2022). All maps were made from the standard map with review No.GS (2020) 4619, downloaded from the standard service website of the National Bureau of Surveying and Mapping Geographic Information. The distances between cities were calculated using the latitudes and longitudes of urban administrative centers.

3.3. Methods

3.3.1. Assessment of Network Resilience

The structures of population migration patterns, with significant correlation and complexity, can be abstracted as a network. Each city is regarded as a node, and the intensity of population migration can be summarized as the directed line edge weights between nodes. The overall structural characteristics of the network are generally investigated using nodes, density, average path lengths, and clustering coefficients. The individual structure features of the network are typically characterized by centrality, transmissibility, and diversity. To reveal and illustrate the features of the network's topological structure and the statistical properties of population migration, the following network analysis indicators were selected:

$$R(x) = f(D, C, L, S, E, V, A) \tag{2}$$

where $R(x)$ is a function of network resilience; D represents the characteristic of consistency, characterized by network density; C represents the characteristic of centrality, which is represented by the degree of centrality; L represents the connectivity feature of the network, measured by the average of independent paths; S denotes the size of the network, as represented by the total number of nodes and edges; network efficiency (E) is used to measure network transmissibility; the average number of independent paths (V) is used to measure the network diversity; and finally, the average clustering coefficient (A) represents the network aggregation. The specific calculation formula is listed in Table 1.

Table 1. Measuring the index of network resilience.

Characteristic	Indicators	Formula	Descriptions
Density	Network density (D)	$D = \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{d(n_i,n_j)}{n(n-1)}$	n is the number of nodes in the network, d is the intensity of population mobility
Centrality	Degree centrality (C)	$C = K_i/N - 1$	K_i is the degree of node i, and N is the number of nodes in the network
Connectivity	Average network distance (L)	$L = \frac{1}{1/2n(n+1)}\sum_{i\neq j} d_{ij}$	d_{ij} is the degree of node i, and N is the number of nodes in the network
Scale	Network size (S)	$S = n + M$	M represents the total number of edges, n is the number of nodes in the network
Transmissibility	Network efficiency (E)	$E = \frac{1}{n(n-1)}\sum_{i\neq j}\frac{1}{D_{ij}}$	D_{ij} is the shortest path length from node i to j
Diversity	Average number of independent paths (V)	$V = \sum_{i\neq j} n_{ij}/n(n-1)$	n_{ij} is the number of independent paths between node i and node j
Aggregation	Average clustering coefficient (A)	$A = 1/N\sum_{i}^{n}\frac{2E_i}{k_i(k_i-1)}$	E_i is the number of paths between a node and its K_i neighboring nodes

NR is calculated quantitatively using the resilience formula proposed by Dixit et al. [20]. Additionally, we modified the formula to calculate the NR of population mobility based on the relationship between seven topology indicators, as shown in (3):

$$R = L \times S \times E \times V/D \times C \times A \tag{3}$$

Using the method of interrupt simulation, changes in network resilience may be described. The role of each city in the overall network was obtained by comparing our simulation to real results.

For the quantitative calculation of anti-interference of network resilience, we simulated changes in the network resilience under disruption due to node failure. Node failure considers impacts, such as an epidemic, on different cities. As targets of the attack, cities are removed, one at a time. This means that a change in the overall network reflects the dynamic processes which determine its degree of resilience, as shown in (4):

$$R_p = R_a - R_b \tag{4}$$

where R_p represents the change of network resilience and R_a and R_b are the network resilience before and after node interruption.

3.3.2. Scenarios of Nodes Disruption

The robustness and resilience of a network are critical to risk reduction and loss mitigation. Network resilience describes the ability of a system to maintain its essential functions in the face of internal disruptions or external changes. To further explore the network resilience of population mobility, we simulated the disruption of connections in cities under the impact of a disruption and observed the changes in their topologies. Two simulation methods expressed the interaction between overall network resilience and city node failures.

It is possible for the failure of a node within a network to result in the removal of that node from the original network. This can result in a fundamental change in the characteristics of the network. Natural disasters such as typhoons, tsunamis, and earthquakes, as well as random events such as urban isolation caused by public health emergencies such as epidemics, can be used to simulate the impact of external shocks on nodes and network connections. Thus, we set the scenario as "**node failure**". In this scenario, nodes are ranked according to their degree of centrality, and failures are simulated sequentially. These urban nodes are removed from the network in turn to form a new network structure, and the topological metrics of the network are calculated.

However, in the "node failure" scenario, only the impact of a specific node city's failure on the overall network may be known, so it is not possible to quantify the importance of the node city or the potential to recover to the original level of network resilience. Changes in network resilience following the failure of different node cities can be attributed to that node city's ability to withstand external shocks. According to our theoretical framework, after a system is hit by an external shock, its internal resistance and defense are enhanced through adaptive mechanisms. A stable equilibrium is achieved through recovery and reorganization. Network resilience and recovery must be distinguished from the resilience of specific features and functions. As a result, we set another scenario, i.e., "**network recovery**", and calculated the network indexes of different nodes after failure as the resilience state, S_1, of the corresponding nodes. By comparing S_1 with S_0, we could determine the impact of urban failure on S_1.

Comparing these two scenarios, the essential difference was that in a "node failure" scenario, node cities disappeared after an attack, and therefore, the overall network evolved and changed. In contrast, although the node cities in "network recovery" scenario were different for each node failure and the network was dynamic, the overall number of connections remained unchanged. By comparing the relative amount of change in resilience before and after the failure, the inherent resistance and resilience of the network became the focus.

The essential difference between these two scenarios is that in Scenario 1, node cities disappear after an attack, resulting in a change in the overall network, while the node cities in Scenario 2 vary each time they fail and the network is dynamic; as such, the overall number of connections remains the same. The disruption scenario simulation was designed to explore the resistance and resilience of the network by comparing the relative changes in resilience before and after a disruption.

3.3.3. Spatial Econometric Regression Model

(1) Variable selection. We selected network resilience (NR) in the three periods of the Spring Festival in 2021 as the dependent variable. According to the gravity model, the strength of inter-city connections is related to the attractive scale of the destination city (economic scale, population size, etc.) and the cost of transportation (such as transportation connectivity, travel time, etc.). After reviewing existing research, 10-factor explanations for the resilience of the urban network were selected. GDP can be interpreted as the measure of economic development of urban areas. The rate of urbanization and the proportion of tertiary industry can serve as measures of urbanization. The total population and total number of employees represent the scale of urban population and employment. The abundance of tourism resources represents the prevalence of urban tourism. Road,

Transport and Car represent the transportation infrastructure conditions. After logarithmic processing, all variables could be used to eliminate dimensional differences (Table 2).

Table 2. Variable selection and descriptive statistics.

Type	Name	Abbreviations	Mean	Std. Dev.	Min	Max
Independent variable	Changes in network resilience	NR	8.142	0.078	8.071	8.485
			8.146	0.077	8.054	8.452
			8.131	0.083	8.067	8.550
Dependent variable	Intensity of population mobility [1]	Mobility	7.894	0.661	6.595	9.386
	Intensity of population mobility [2]		6.944	0.752	5.638	8.709
	Intensity of population mobility [3]		6.997	0.547	5.471	8.012
	Gross domestic product	GDP	8.266	0.918	6.746	10.564
	Total population at the end of the year	POP	6.134	0.677	4.753	7.819
	Urbanization rate	UR	0.664	0.113	0.420	0.893
	Total number of employees	Lab	4.877	1.232	1.515	6.617
	Proportion of tertiary production	Is	0.523	0.085	0.423	0.883
	Highway mileage	Road	9.357	0.484	7.565	10.130
	Passenger transport volume	Transport	7.862	0.874	6.161	9.951
	Motor vehicle ownership	Car	4.591	0.856	3.012	6.112
	Number of domestic tourists	Tourist	8.331	0.810	6.923	10.069

Intensity of population mobility [1–3] during the return, leaving, and ordinary periods, respectively.

(2) Spatial model. Considering the spatial dependence of intercity mobility, we used a spatial econometric model to explain the influencing factors and detect the spatial effects of network resilience in the YRDR during the Spring Festival. The spatial error model (SEM) and the spatial lag model (SLM) are principally used to describe spatial correlations [36]. The SLM supposes that the spatially averaged weight of the adjacent *NR* partially reduces the value of NR observed in city *i* due to spatial interactions. The SLM is expressed as:

$$lnNR_{i,t} = \rho w_{i,t} lnNR_{i,t} + \beta_i x_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (5)$$

The SEM integrates spatial relationships based on the spatial dependence between the error terms associated with local and neighboring cities. The SEM is defined as:

$$lnNR_{i,t} = \beta_i x_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t},\ \varepsilon_{i,t} = \lambda w_{ij} \varepsilon_t + \mu_{i,t} \quad (6)$$

where $lnNR_{i,t}$ stands for the *NR* of city *i* at time *t*; $x_{i,t}$ is the explanatory variable; β_i is the coefficient to be estimated; ρ_i is the coefficient of spatial autoregressive; λ is the coefficient of spatial error; ε_t indicates the impact of the shock on neighboring cities; μ_i and γ_t are the individual and time effects; and $\mu_{i,t}$ is random error.

4. Results

4.1. Spatial Patterns within Population Mobility Networks

We constructed connection networks and linkages based on the intensity of population mobility among cities. The degree of centrality of each node was further analyzed, as this reflects the radiation effect of a city node on others in the network. In our study, a city is considered a regional central city with a high degree of centrality, strong convergence or evacuation ability, and high communication ability. The spatial pattern of each connection network and node degree centrality is presented in Figure 5.

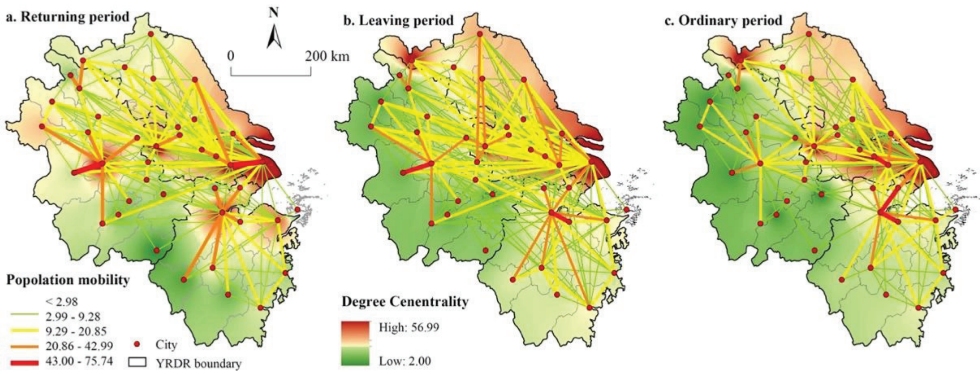


Figure 5. Spatial patterns of population flow networks and node degree centrality in the Yangtze River Delta Region.

The intensity of population flow between cities at the first level (43.00–75.74) presented scattering. Strong linkages existed between the core city and its adjacent nodes, such as Shanghai–Suzhou, and Hefei–Lv'an. The second level (20.86–42.99) presented an axis of Shanghai–Suzhou–Wuxi–Changzhou and two clusters around Hangzhou and Hefei. The third level (9.29–20.85) reflected the association between provincial capital cities and other cities within the same province. About 83% of all city linkages were at level four (<2.98), indicating that the intensity of most cities is low, and most city connections are relatively fixed. In the ordinary period, strong connections between cities in terms of daily population flow are mainly regional in nature.

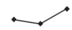
During the return period, the top 10 cities were as follows: Shanghai, Nanjing, Suzhou, Hefei, Hangzhou, Wuxi, Ningbo, Changzhou, Yangzhou, and Fuyang. Spatially, these cities formed several obvious regional high-value agglomeration areas. In the leaving period, cities in Jiangsu Province were high-value areas for population mobility. The top 10 cities were as follows: Shanghai, Suzhou, Nanjing, Hangzhou, Hefei, Wuxi, Ningbo, Fuyang, Changzhou, and Yangzhou. The provincial capital cities became the nodes with the greatest population flow during this period. At the same time, some traffic node cities also had a higher degree of centrality than before. In the ordinary period, which was roughly the same as the leaving period spatial pattern type, the difference was that the degree of interconnections between cities had weakened.

4.2. Assessment and Characteristics of Network Resilience

Changes in the network topology indexes were diverse in the different periods, so the network resilience tended to be stable over time. As shown in Table 3, the centrality and connectivity of the overall network gradually decreased, while the density, size, and aggregation of the network first increased and then decreased, presenting an inverted "V" trend. The average daily passenger volume in the return and leaving periods was much higher than usual.

The centrality and connectivity of the network were enhanced when mobility intensity was high and tended to be flat when liquidity decreased. This could be verified with the spatial variation characteristics of the previous network connection pattern. The network density, size, and aggregation should change, because the increase in population mobility during the Spring Festival leads to more paths with similar distances. This linkage did not reveal strong flow intensity, and the spatial pattern did not significantly increase in terms of the number of strong connections. However, it changed the overall network topology and increased network redundancy, impacting network resilience.

Table 3. Network structure resilience.

Topological Index	***ND***	***NC***	***NL***	***NS***	***NA***	***NE***	***NV***	***NR***
Return period	0.214	0.684	2.084	392	0.476	0.763	4.929	4672.070
Leaving period	0.231	0.661	2.004	420	0.518	0.740	4.332	3997.759
Ordinary period	0.210	0.614	1.964	389	0.476	0.824	4.530	3970.058
Trend								

ND is the network density; *NC* is the network degree centrality; *NL* is the network connectivity; *NS* is the network size; *NA* is the average clustering coefficient; *E* is the network efficiency; *NV* is the average number of independent passageways; *NR* is network resilience.

In addition, the transmissibility and diversity of the network decreased first and then increased, but notably, network transmissibility was the highest in the ordinary period, i.e., it increased from 0.763 to 0.824. The diversity index decreased from 4.929 to 4.530 at the end of the Spring Festival. The changes in network diversity were mostly caused by the decrease of population flow through a decline of physical connections, thus obviously leading to the deterioration of the fault tolerance of the network. While there was a lot of population movement during the Spring Festival, this also encouraged connections to the city, which translated into a slightly higher than usual network connectivity. When a path was interrupted, other paths could ensure the normal function, thus effectively maintaining the stable operation of the network. Overall, the level of network toughness gradually stabilized from 4672.07 in the return period to 3970.058, with no significant change in the leaving and ordinary periods.

4.3. Network Resilience Changes under Disruption Scenarios

4.3.1. Changes in Overall Network Resilience: "Node Failure"

Figure 6a–g shows the proportion of failed city nodes and the changes in the network topology index. The network topology indexes showed different trends in three time periods as the node failure rate increased. Specifically, network density (ND) and network size (NS) are linked to the nodes and edges, so node failure will cause them to decrease. Overall, both indices decrease as the node failure rate increases. As the proportion of intentional attacks increases, network centrality (NC) progressively decreases. During the return period, when the node failure rate was 0.8, NC was reduced to 0 and the network failed. In the ordinary period, the whole network failed after 0.9, implying that the anti-attack ability of network centrality is more robust in the "normal" period than during the Spring Festival.

The network connectivity (NL) and diversity (NV) indices initially increased and then decreased as the degree of node failure increased. Both achieved the highest values following the failure of some nodes in connection with the network. The change in network efficiency (NE) also confirmed this, with the difference being that NE increased first after node failure decreased. When the attack rate reached about 70%, the network suddenly failed and dropped to 0. Network aggregation (NA) decreased and increased, becoming invalid in the end.

Figure 6h illustrates how the NR changes in a node failure scenario. As network nodes fail, the NR increases accordingly. With 20% of nodes failing during the leaving period, the NR reached the highest level, while in the other two periods, the NR was 5% and 12%. Clearly, the NR maintained a relatively stable rate during the return period. However, the network collapse was accelerated when nodes failed, as it had greater volatility during the leaving and ordinary periods.

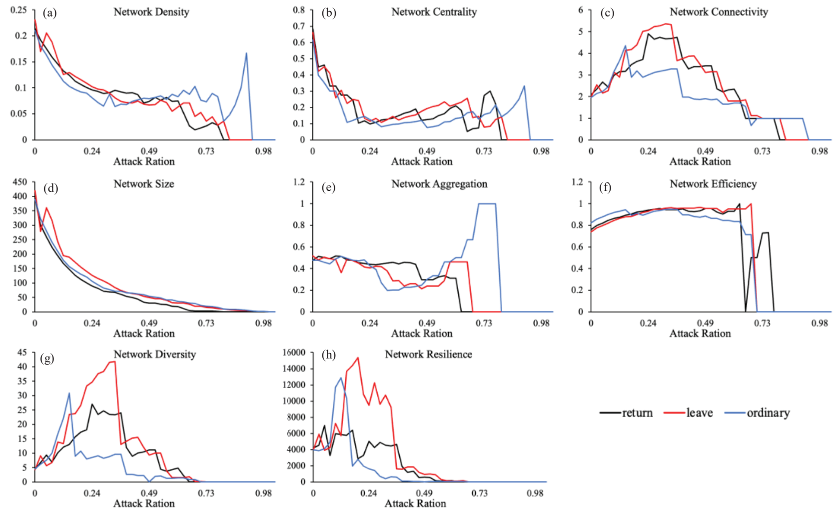


Figure 6. Changes in complex network topological indexes under different disruption scenarios.

4.3.2. Changes in the Resilience of Node Cities: "Network Recovery"

The second simulation method considered the impact of COVID-19 on different city nodes. We simulated the threat of a public emergency event using the nodes within the network as the attack object, as well as the interruption of the network every time a node was lost. The design involved simulated attacks on 41 nodes. Likewise, the topology indicators and NR were updated. Afterwards, each node was removed or isolated until all the nodes in the network had been removed.

A positive correlation exists between urban nodes and centrality in the YRDR, showing the spatial characteristics of the agglomeration along the transport corridor. Network resilience (NR) and degree of city centrality (NC) were divided into five levels, as shown in Figure 7. First- and second-level cities, such as Shanghai, Suzhou, Wuxi, Nanjing, and Hefei, were primarily provincial capitals and regional core cities, forming a distribution trend along two distinct axes: Shanghai–Nanjing and Shanghai–Hangzhou. With the increase in population flow, this phenomenon became more pronounced, most notably in the return period. Thus, development along the Yangtze River Economic Belt axes is key to achieving the sustainable network in the YRDR.

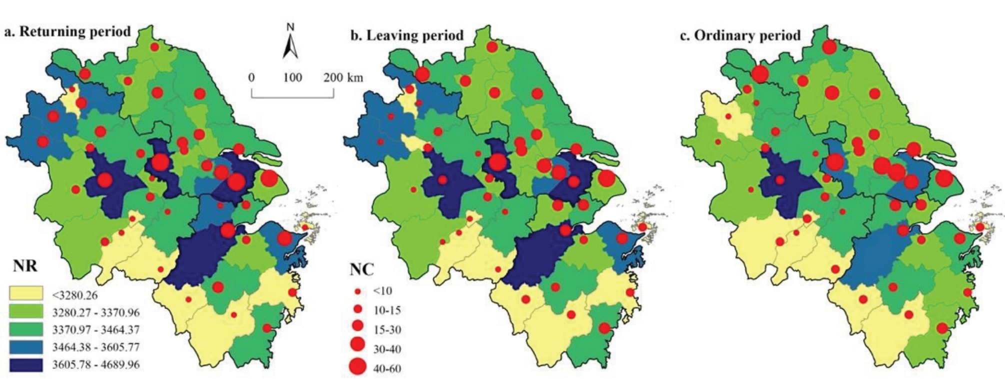


Figure 7. Spatial pattern of the impact of urban node failure on network resilience.

4.3.3. Variation of Node Anti-Interference of Network Resilience

Furthermore, different city nodes present different levels of anti-interference between NRs, which means that the failure of other nodes weakens the resilience of city nodes. However, only one city typically had the highest levels of resilience when the resilience of each city was examined under a state of maximum disturbance. As shown in Figure 8, with the interruption of network nodes, the attenuation degree of node resilience presented differences. During the return period, Huaibei, Zhoushan, Chizhou, Quzhou, and Lishu experienced the greatest declines, while Nanjing, Hefei, and Hangzhou saw relatively little change. The spatial distribution pattern decreased from the periphery to the center. The situation during the leaving period was similar. Due to the increase in population mobility, peripheral cities increased their network resilience and were highly vulnerable to the impact of node failures. In the ordinary period, this phenomenon was more prominent: the attenuation of network resilience decreased from outside to inside, and the core cities demonstrated the least volatility.

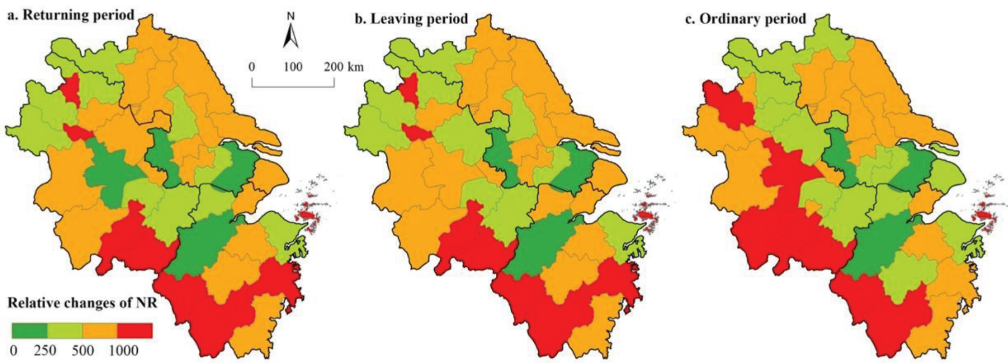


Figure 8. Spatial pattern of attenuation in node resilience.

Another crucial node related to resilience in the YRDR is called the "vulnerability node". The resilience of cities is likely to be significantly attenuated by the failure of other cities. Vulnerable nodes reduce the resilience of the overall network. The spatial distribution of vulnerability nodes also showed agglomeration characteristics. Most nodes with significant declines were in the Anhui and Zhejiang provinces, forming agglomeration areas with apparent vulnerabilities in the periphery. The cities in Jiangsu Province and Shanghai demonstrated higher fault tolerance and a more robust ability to resist shock.

4.4. The Mechanism of Urban Networks Resilience

We selected and analyzed factors influencing the resilience of migration networks in different periods. Firstly, a collinearity test was conducted to eliminate variables with multicollinearity. Finally, eight independent variables, i.e., GDP, number of employees, urbanization rate, administrative level, road density, aviation, high-speed rail, and tourism resource richness, were retained. According to the collinearity diagnosis results, the final independent variable variance inflation factor (VIF) was less than five, and tolerance was greater than 0.30, indicating no obvious collinearity between the respective variables. By comparing the R2, logarithmic likelihood, AIC, and SC values of the three models (Table 4), it was found that the SLM model had the most significant logarithmic likelihood and the smallest AIC and SC values, making it suitable for identifying factors which influence intercity travel.

Table 4. Spatial econometric model results for network resilience.

	OLS		SLM		SEM	
Variables	**Coefficient**	***Z* Value**	**Coefficient**	***Z* Value**	**Coefficient**	***Z* Value**
W_NR			−0.029 ***	−3.783		
Lambda					−0.399 *	−1.618
Mobility	0.060 **	2.195	0.084 ***	4.036	0.068 ***	3.226
GDP	−0.138	−2.589	−0.178 ***	−4.440	−0.146 ***	−3.367
POP	−0.020	−0.340	−0.022	−0.497	−0.018	−0.374
UR	0.570 **	2.551	0.692 ***	4.201	0.608 ***	3.435
Lab	0.038 **	2.731	0.044 ***	4.241	0.035 ***	3.266
Is	0.105	0.528	0.128	0.888	0.134	0.813
Road	0.056 ***	1.835	0.104 ***	4.092	0.104 **	2.370
Transport	0.026	1.417	0.006	0.427	0.023	1.517
Car	0.046	1.472	0.085 ***	3.427	0.043	1.627
Tourist	0.034 *	1.625	0.032 **	2.115	0.029 **	1.840
Constant	7.088 ***	22.167	6.905 ***	29.216	7.083 ***	25.535
R^2	0.685		0.766		0.701	
LogL	70.620		76.774		71.087	
AIC	−117.241		−127.547		−118.174	
SC	−96.678		−105.271		−97.611	

W_NR is the coefficient of spatial autoregressive; Lambda is the coefficient of spatial error. The symbols ***, **, and * denote the significance at 1%, 5%, and 10%, respectively.

The spatial lag coefficient of W_NR was −0.029; this result passed the 99% significance test, indicating that urban network resilience has noticeable spatial spillover effects. The degrees of network resilience of adjacent cities influence each other. Overall, if the resilience of a node city increases by 1%, those of the surrounding adjoining node cities will decrease by 0.029%. This shows that network resilience has strong regional linkages, and the cascading effect between nodes reduces the overall resilience.

According to the results of the SLM, five independent variables, i.e., the mobility of the urban population (mobility), urbanization rate (UR), the total number of employees (lab), road density (road), and the tourism (tourist), passed the significant level test, and all were positively correlated with urban resilience. The scale of urban population flow (mobility) indicated the population migration situation during the period; the higher the value, the greater the interconnection between cities. When mobility between cities increased, the resilience of the city network was the highest. The coefficient of the urbanization rate (UR) was the largest at 0.570; this result passed the 5% significance test. Cities with higher urbanization levels have advantages in terms of infrastructure and emergency support and have played a significant role in enhancing urban resilience. The total number of employees (lab) reflects the labor force in each city. The return of the labor force after the Spring Festival is the main reason for population migration. Its coefficient was 0.038; this result has passed the 5% significance level test. The increase in the number of laborers returning to their hometowns during the Spring Festival also improved the ability of the network to cope with more uncertain risks. The "road" and "tourist" variables passed the 1% and 10% significance level tests, respectively.

On the one hand, this shows the essential supporting role of intercity transportation connectivity. Traveling abroad during the Spring Festival holiday will also affect network resilience. On the other hand, the impact of this is relatively small, indicating that people will reconsider travel risks due to restrictions against the background of the normalization of epidemic prevention and control.

5. Discussion

5.1. Identifying Dominant and Vulnerable Nodes

It is important to understand how the failure of a dominant and vulnerable city node in the YRDR affects the resilience of the network structure. The process of identifying this node is based on the comprehensive distribution of NR over different time periods. Four dominant nodes and seven vulnerable nodes, each heavily influencing the network structural resilience in the YRDR, were found. Nanjing, Suzhou, Hangzhou, and Hefei are the four dominant node cities with high levels of centrality and control. Each of these has a relatively high degree of economic development and a comprehensive transport center.

There were seven vulnerable nodes (Huaibei, Tongling, Huangshan, Quzhou, Lishui, Taizhou, and Zhoushan) that showed specific agglomeration distribution characteristics in space, i.e., mostly peripheral or border cities in the YRDR. Spatial aggregation leads to a regional lock-in effect. When a node reduces in scope, it does not significantly impact the larger regional environment. This could result in insufficient resource replenishment, unbalanced supply and demand, and uneven development in small areas. Most such nodes were far away from provincial capital cities or at the junctions between provinces. Limited by inadequate administrative barriers and transport infrastructure, such cities may become "dead cities".

5.2. Optimization for Improvement of Resilience

When a dominant node is paralyzed during a crisis, it interferes tremendously with the resilience of the network structure. Meanwhile, vulnerable nodes are the best indicators of network resilience. Uncertainty about the global spread of COVID-19 persists. Various phenomena have made us realize that the coordinated management of public health emergencies in the YRDR still needs to be strengthened [37]. Therefore, we propose a cross-scale collaborative spatial governance system, the "Region-Metropolitan-City" (Figure 9). Through multi-level linkages, this approach can address the uncertain disturbances caused by the network cascading effect and improve the resilience of a regional network.

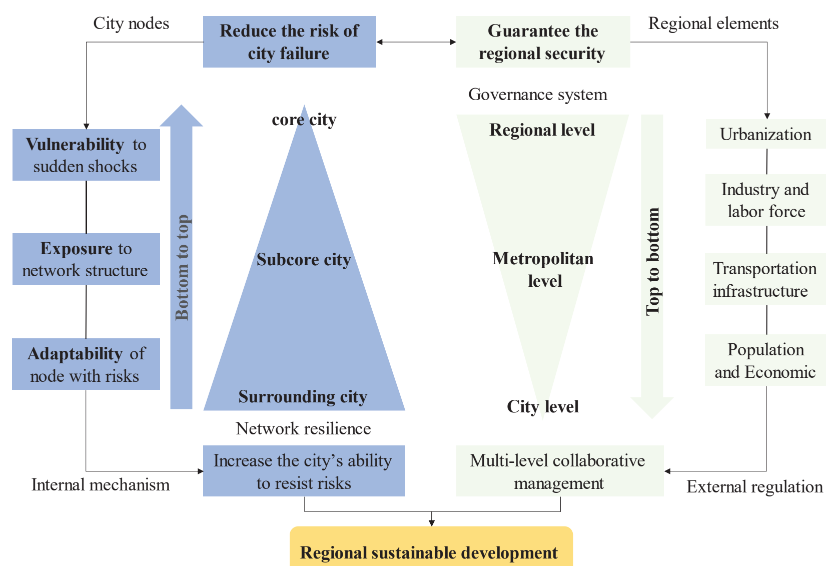


Figure 9. Optimization of network resilience framework.

Diverse and frequent elemental flows can lead to regional perturbations or collapses due to the strengthening of regional negative externalities. Current territorial spatial planning focuses on urban resilience; its attention to regional resilience is by no means sufficient. Regional networks need to demonstrate resilience to external disruptions to ensure regional coordination, stability, and sustainable development [38,39]. Hence, the regional integration of various elements (urbanization, industry, transportation, infrastructure, and socioeconomic) and different scenarios (disruption and external shocks) should be considered in future spatial planning. The failure probability of node cities can be reduced by increasing the abilities of nodes to resist risks. At the same time, by building a cross-scale collaborative management system to ensure the overall security, this integrated approach will greatly enhance the resilience of city nodes and regions. Therefore, node improvement and system optimization are two important pathways to enhance regional resilience.

5.3. Limitations and Further Works

While we have analyzed network resilience from the perspectives of CAS and CN, there are still some limitations that could be further investigated, including the following: We were not able to obtain population mobility data in the YRDR for 2020 or 2022, so this paper could not verify the difference in the impact of the COVID-19 on urban network resilience through comparisons with historical periods. We only simulated the spatial characteristics of regional network resilience under disruption based on data, which may have some effects on our policy implications. Due to the suddenness and randomness of public health emergencies, we did not consider random combinations of different city failures. Rather, we just simulated changes in network resilience under the cumulative failure of each node city, along with the decline in resilience under each node failure, to better understand which cities were the most vulnerable points and how they could be managed more effectively. Additionally, we did not consider how network resilience changes under different combinations of city failures, which should be the subject of a future study. Our objectives were to introduce a complex perspective for the evaluation of network resilience and to assess whether neighboring nodes have a mutual influence on network resilience. As a result, the groundwork has been laid for the next combination of scenarios and network cascade effects under random disruption in different cities within the network.

The promulgation of the Yangtze River Delta Integration Policy has injected new vitality into regional interconnectivity and social-economic development. We could consider incorporating regional resilience improvement and vulnerability governance in future planning practices, which could be improved in the following ways: (1) through exhaustive studies of the risk response capabilities of non-core cities and quantitative analyses of other modes of population flow when non-core cities are disturbed; (2) by comprehensively assessing changes in the resilience of population mobility networks and the spread of epidemics, disaster risks, and government control measures; and (3) by discussing in more detail how long it takes the system to recover from a disturbed state to a steady state and the degree to which different policies influence this transition.

6. Conclusions

This paper proposes a conceptual framework for network resilience using complex adaptive systems in combination with complex network analysis. In contrast with previous studies, the theoretical model was applied to an actual analysis through a network resilience evaluation of population mobility in the Yangtze River Delta region, demonstrating the rationality of the theoretical assumptions. Using node failure simulation and spatial effect analysis, we also proposed a governance strategy to optimize and improve network resilience in the region. The major conclusions are as follows:

First, the intensity of travel during the Spring Festival in 2021 had obvious characteristics over time. Due to restrictions related to the COVID-19 pandemic, the population mobility before the holiday was less than after the holiday. Second, the network resilience in the YRDR was greatly affected by its topological characteristics, which are closely related to urban connections. The network structure was found to be unstable, and the interruption caused responsiveness and resilience to synchronous decline. NR showed a dependence on transportation corridors, and the urban nodes that significantly interfere with the overall resilience of the network structure were mainly concentrated on axes that were consistent with the Shanghai–Nanjing and Shanghai–Hangzhou development axes. Third, disruption simulations can be used to further identify critical elements that affect the resilience of network structures. With the failure of node cities, network resilience first rises and then declines; in the YRDR, population mobility has a certain degree of redundancy. Finally, the network resilience in the YRDR has a negative spatial spillover effect. The factors which affected NR during the Spring Festival included urban scale such as urbanization rate and labor force, as well as traffic connectivity. Tourism attractiveness and population size gradually decreased as a result of the COVID-19 pandemic. Generally, the most effective means to increase the resilience of regional networks are the acceleration of urbanization and the enhancement of local transportation infrastructure.

Overall, our research contributions are mainly reflected in the following aspects: at the methodological level, we propose a method by which to assess regional network resilience using disruption scenario simulations and spatial effects analyses to identify vulnerabilities and key influencing factors; at the theoretical level, we present a theoretical framework for measuring regional complex network resilience, which enhances the potential of theoretical analyses of regional and urban network resilience. Specifically, our method treats network resilience as a system structure, rather than as a collection of characteristics and relationships. The findings of this study also demonstrate that via the construction of a cross-scale collaborative spatial governance system, uncertainty disturbances caused by network cascading effects can be resolved and insights can be gained regarding the sustainability of other regions.

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Article

Spatiotemporal Dynamics and Driving Forces of Land Urbanization in the Yangtze River Delta Urban Agglomeration

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Abstract: Land urbanization is a comprehensive mapping of the relationship between urban production, life and ecology in urban space and a spatial carrier for promoting the modernization of cities. Based on the remote sensing monitoring data of the land use status of the Yangtze River Delta urban agglomeration collected in 2010 and 2020, the spatial differentiation characteristics and influencing factors of land urbanization in the area were analyzed comprehensively using hot spot analysis, kernel density estimation, the multi-scale geographically weighted regression (MGWR) model and other methods. The results indicated the following: (1) From 2010 to 2020, the average annual growth rate of land urbanization in the Yangtze River Delta urban agglomeration was 0.50%, and nearly 64.28% of the counties had an average annual growth rate that lagged behind the overall growth rate. It exhibited dynamic convergence characteristics. (2) The differentiation pattern of land urbanization in the Yangtze River Delta urban agglomeration was obvious from the southeast to the northwest. The hot spots of land urbanization were consistently concentrated in the southeastern coastal areas and showed a trend of spreading, while the cold spots were concentrated in the northwest of Anhui Province, showing a shrinking trend. (3) Compared with the GWR model and the OLS model, the MGWR model has a better fitting effect and is more suitable for studying the influencing factors of land urbanization. In addition, there were significant spatial differences in the scale and degree of influence of different influencing factors. Analyzing and revealing the spatiotemporal characteristics and driving mechanism of land urbanization in the Yangtze River Delta urban agglomeration has important theoretical value and practical significance for the scientific understanding of new-type urbanization and the implementation of regional integration and rural revitalization strategies.

Keywords: land urbanization; new-type urbanization; rural revitalization; multi-scale geographically weighted regression (MGWR); Yangtze River Delta urban agglomeration

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1. Introduction

Urbanization is a product of the industrialization era, including major changes in economic structure, production methods, lifestyles and land use methods. It is also the result of the long-term accumulation of population aggregation and urban construction [1–5]. Unlike the urbanization development of developed countries in Europe and America, China's urbanization realized the 200-year development process experienced by developed countries in Europe and America in more than 40 years [6,7]. China's urbanization is based on the top-level design under the growth model. Especially after entering the 1990s, due to the expectation of China's rapid development and the eagerness to achieve success in the actual command process, the decision-making level often excessively promoted urbanization, with a focus on the digital and physical dimensions of economic growth and spatial expansion [6,8,9]. The urban built-up area caused by the rapid expansion of urban space will become larger and larger, leading to incurable urban diseases, and some "empty cities" and "ghost towns" are likely to appear in the future. Urban planning should gradually shift from expansionary planning to limiting urban development boundaries and optimize the planning of the space structure [8,9]. Land urbanization, as the concrete manifestation of urbanization in space, is mainly manifested in the transformation of agricultural land into urban construction land, which has become the focus of both scholars and the government [10–12]. According to the statistics of the *China Urban Construction Statistical Yearbook*, from 2010 to 2020, the area of urban construction land in China increased from 39,758.4 km^2 to 58,355.3 km^2, an increase of 46.77%. However, the rapid development of urbanization and the disorderly spread of urban land have been criticized, and they have been repeatedly banned in various places. As a result, the conflict between urban production space (it is a specific functional area where people engage in production activities), living space (it is the space for people's daily life activities) and ecological space (it is a regional space with an ecological protection function that can provide ecological products and ecological services) [13] has become increasingly intensified, posing a threat to the sustainable development of cities [14–16]. China's urbanization problem is more complicated. On the one hand, the leverage force caused by the difference in land rent makes the relatively low suburban prices the main attraction of urban spatial development, which leads to the disorderly extension of urban boundaries without an effective control mechanism [17]. On the other hand, the deep reasons are the financial decentralization and the performance appraisal system aiming at economic growth under China's long-term urban–rural dual system [18]. Under the influence of multiple internal and external factors, the long-term unequal exchange of capital, land, labor and other elements between urban and rural areas makes the urban land expansion rate ahead of the urban population growth rate a common disease in most cities [19]. In November 2019, the General Office of the Central Committee and the General Office of the State Council issued the "Guiding Opinions on the Overall Delineation and Implementation of Three Control Lines in National Land and Spatial Planning", which clearly stated that the three control lines of urban development boundaries, permanent basic farmland and ecological protection red lines should be adjusting the economic structure, planning the development of the industry and promoting the insurmountable red line of urbanization [20]. Under the strong control of the three major land and space red lines, the urban development path that traditionally relies on the disorderly expansion of extension space will be well controlled [21].

With the advent of the era of global cities, the development of each city does not exist in isolation. The flow of people, logistics, information and capital connects different cities in the process of spatial flow [22]. Urban agglomeration has become the main form of urbanization development, with a high level of land urbanization [23,24]. Scholars from home and abroad have conducted much research on the pattern of land use change in urban agglomerations and metropolitan areas. Bosch et al. [25] explored the spatial and temporal patterns of land use change in three Swiss urban agglomerations through landscape indicators and growth patterns; Wu et al. [26] performed a comparative analysis of the metropolitan regions of Phoenix and Las Vegas and revealed that, throughout the twentieth century, the two agglomerations showed a strikingly similar trend towards a landscape that is more diverse in land use, fragmented in structure and complex in shape; Dutta et al. [27] used geospatial indices to explore the dynamics of urban expansion in the English Bazar Urban Agglomeration, revealing that the northwest and southwest parts of the English Bazar UA are experiencing a rapid increase in sprawl. Li et al. [28] used mathematical statistics and spatial analysis methods to analyze the change process of urbanization, coupling co-scheduling and ecological risk response pattern in the Yangtze River Delta, and found that the coupling coordination degree of population, land and economic urbanization in the Yangtze River Delta is increasing, and the ecological risk is weakening. Niu et al. [29] studied the evolution of the interactive relationship between urbanization and land use transformation in the Yangtze River Delta and found that rapid urbanization exacerbates the trend of land fragmentation, promotes the rapid expansion of construction land and hinders the further development of urbanization. The Yangtze River Delta urban agglomeration is one of the regions with the most active economic development, the highest level of urbanization and the greatest degree of land development in China. It has consistently been a major focus among academics both domestically and internationally [30,31]. Revealing the spatial and temporal evolution patterns and influencing factors of land urbanization in the Yangtze River Delta urban agglomeration is of great significance in guiding the healthy development of urbanization in other urban agglomerations and similar regions in China and the world and in promoting the sustainable development and utilization of urban land resources.

Among the relevant research progress at home and abroad, scholars' attention and discussion regarding land urbanization mainly focus on three aspects. The first aspect is the concept definition and measurement evaluation of the land urbanization level. Scholars have interpreted the concept of land urbanization from the perspectives of land use form transformation [32] and the nature of rights [33]. Li et al. [34] pointed out that the definition of the connotation of land urbanization should serve the coordination and matching relationship between land urbanization and population urbanization. For the calculation of the level of land urbanization, the single index method (the proportion of construction land or built-up area to the total area) [35,36] and the other composite index method (the quality of land urbanization) [37] are widely used. Some scholars also measured the process of land urbanization from the aspects of land structure, input and output [29,38,39]. The second aspect is the research on the coordination relationship between land urbanization and population urbanization and its regional differences [40]. There is a consensus that land urbanization is ahead of population urbanization on a national scale, but this unbalanced relationship appears in different regions or cities [41]. Some scholars found that the coupling relationship between land and population urbanization has periodic characteristics [42,43]. In recent years, the imbalance between the two has eased, and some areas have even developed land. Urbanization lags behind the trend of population urbanization [44]. The third aspect is research on the driving mechanism of land urbanization. China's specific fiscal decentralization and dual urban–rural land management system are recognized as the fundamental driving forces of land urbanization [45,46]. However, from the perspective of "human–land coordination", factors such as natural geographical conditions (including terrain conditions and annual precipitation) and social and economic development (including economic development and social basic conditions) [47] can also explain the changes in the spatial pattern of land urbanization to a certain extent. Zhou et al. [48] addressed the impact of population, economy, social public services and space on rural in situ urbanization in the Beijing–Tianjin–Hebei region. Gao et al. [49] revealed the impact of six major influencing factors, foreign direct investment (FDI), labor force, government competition, system, population and the employment housing relationship, on urban land expansion in the Yangtze River Delta. Traditional correlation analysis [50], multiple regression analysis [51] and principal component analysis [52] have often been used in the study of driving factors, but they ignore the regional differences between research units, and it is difficult to characterize the spatiality of the data fully.

Academic research has expanded the multi-dimensional perspective of land urbanization analysis, which is of great significance for profoundly understanding the pattern of land urbanization and its driving forces and then optimizing the pattern of urban and rural land use [53–55]. Most of the existing studies established global models based on statistical data and failed to consider the spatial heterogeneity and non-stationarity within the study area [47,56,57]. Furthermore, the spatial variation characteristics and spatial distribution rules of the research objects cannot be reflected, resulting in strong universality and insufficient pertinence of the policy recommendations proposed by the research. Urban agglomerations are the main body of urbanization [58]. They play an important role in optimizing the urban spatial structure, promoting the construction of new urbanization and promoting the development of regional integration [59,60]. However, according to the current research progress, the systematic research on the development dynamics, spatial pattern and formation mechanism of land urbanization in urban agglomerations is still insufficient [36,48,49]. The 19th National Congress of the Communist Party of China also clearly proposed that the urban agglomeration should be the main body with which to build an urban pattern of coordinated development for large, medium and small cities and small towns [61]. Therefore, based on the remote sensing monitoring data of China's land use status, this paper quantitatively analyzes the spatiotemporal characteristics and formation mechanism of land urbanization in the Yangtze River Delta urban agglomeration in order to deepen the theoretical research on rural geography and land use and to promote urban–rural integration and provide a new scientific basis for strategic decisions such as those regarding urbanization.

This study aims to reveal the spatiotemporal dynamics of land urbanization in the Yangtze River Delta urban agglomeration and explore its driving mechanism. This article is divided into five sections. Section 2 presents the study area, study methodology and data sources. The Section 3 introduces the spatiotemporal dynamics of land urbanization in the Yangtze River Delta urban agglomeration from 2010 to 2020, and the Section 4 discusses the multi-scale effects and spatial heterogeneity of different influencing factors based on the MGWR model. Section 5 compares key findings with previous research, makes policy recommendations and provides a brief conclusion.

2. Materials and Methods

2.1. Study Area

The Yangtze River Delta urban agglomeration is an important intersection between the "Belt and Road" and the Yangtze River Economic Belt. It has a pivotal strategic position in the overall situation of China's national modernization and development. It is an important platform allowing China to participate in international competition, an important engine for economic and social development. The center of the Yangtze River Economic Belt is also one of the regions with the best urbanization foundation in China. The study area falls within the scope of the central area delineated by the "Outline of the Yangtze River Delta Regional Integrated Development Plan" issued by the Central Committee of the Communist Party of China and the State Council in December 2019, including 9 cities in Jiangsu Province (Nanjing, Suzhou, Wuxi, Changzhou, Zhenjiang, Yancheng, Nantong, Yangzhou, Taizhou), 9 cities in Zhejiang Province (Hangzhou, Jiaxing, Shaoxing, Ningbo, Jinhua, Huzhou, Zhoushan, Taizhou, Wenzhou), 8 cities in Anhui Province (Hefei, Maanshan, Wuhu, Tongling, Anqing, Chuzhou, Xuancheng and Chizhou) and Shanghai. The Yangtze River Delta urban agglomeration has a total area of 223,800 km^2 and a population of approximately 225 million. The topographic features of the Yangtze River Delta urban agglomeration are high in the southwest and low in the northeast, with an elevation range of −83.31~1736.98 m (Figure 1), including a total of 127 counties. Due to the incompleteness of the land use remote sensing monitoring data of Shengsi County, it was omitted from the study, and the study area thus included 126 counties.

2.2. Data Sources

The research used the urban and rural construction land (including towns, industrial and mining areas, rural settlements, transportation and other construction land) in the remote sensing monitoring data of China's land use status collected in 2010 and 2020, mainly from the Resource and Environment Data Center of the Chinese Academy of Sciences, covering 30 m across the country. We constructed a spatial distribution map of land use types with high resolution. The socioeconomic data required for the analysis of influencing factors came from the 2011 and 2021 *China Counties Statistical Yearbook* (County and Cities volume). The population density data came from the WorldPop population dataset (https://www.worldpop.org/ accessed on 10 January 2022); the average annual precipitation, DEM and other data were also from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn accessed on 10 January 2022), and density of roads data came from OpenStreetMap.

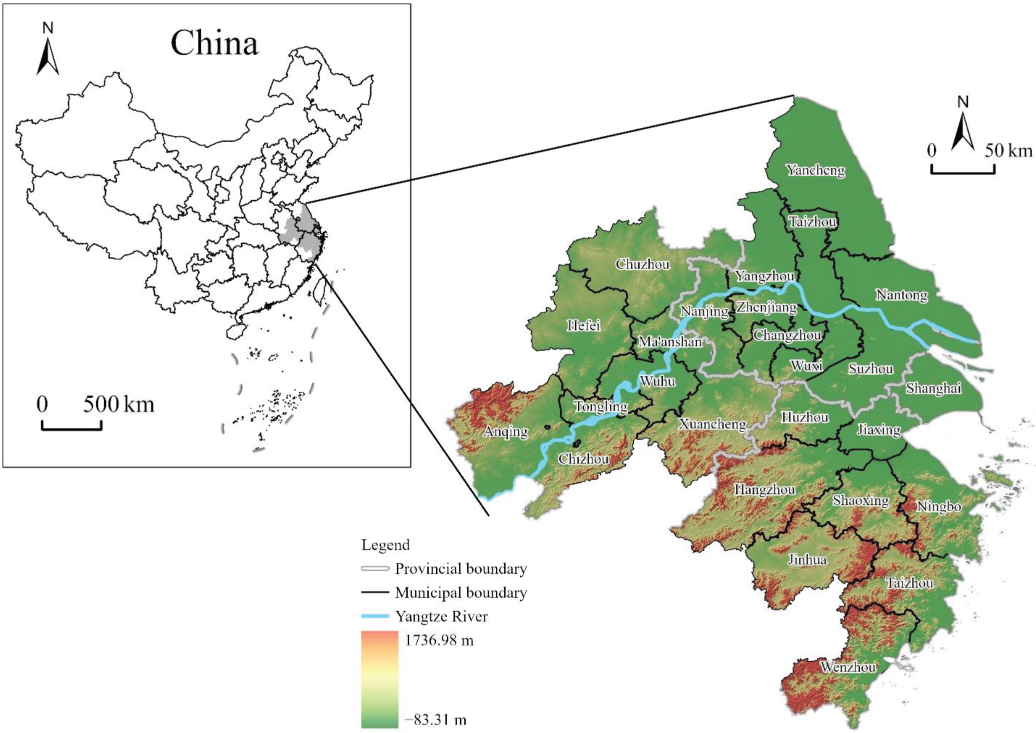

Figure 1. Location of the study area.

2.3. Methods

(1) Land Urbanization Evaluation Index

With reference to the land non-agriculturalization index [62] and the quality of land urbanization [37], the index of land urbanization rate (LUR) in the counties of the Yangtze River Delta urban agglomeration was constructed, i.e., the ratio of urban industrial and mining land and transportation land to the total scale of urban and rural construction land. The indicators not only describe the level of land urbanization, but also reflect the changes in the land use structure in the process of county urbanization [57]. The formula is as follows:

$$LUR = \frac{ul + il + tl}{ul + il + tl + rl} \tag{1}$$

where ul is the scale of urban land, il is the scale of industrial and mining land, tl is the scale of transportation land and rl is the scale of rural residential land. Based on the spatial analysis function of ArcGIS Pro 2.8 software (https://www.esri.com/zh-cn/arcgis/products/arcgis-pro/trial (accessed on 10 January 2022)), the land urbanization pattern of each county in the Yangtze River Delta urban agglomeration from 2010 to 2020 was visualized.

(2) Spatial Autocorrelation Analysis

Spatial autocorrelation analysis can reveal the spatial distribution of a single attribute of the research object and quantitatively measure its correlation degree [63]. The global spatial autocorrelation, which uses Moran's I index [64], was used to identify whether the spatial distribution of land urbanization in the Yangtze River Delta urban agglomeration had spatial agglomeration; the local correlation analysis used the "local Getis-Ord's index" [65]. The cold spots and hot spots of land urbanization in the Yangtze River Delta urban agglomeration were identified, and the conceptualization of spatial relationships was set with CONTIGUITY_EDGES_CORNERS.

(3) Kernel density estimation

Kernel density estimation is a non-parametric estimation method [66,67] that uses continuous density function curves to describe the distribution of random variables. Kernel density estimation uses a smooth peak function to fit the sample data and uses a continuous density curve to describe the distribution of random variables, which has the advantages of weak model dependence and strong robustness. In this study, epanechnikov was selected as the kernel function, and the bandwidth was 0.0749.

(4) Index selection and model construction of influencing factors

Considering the particularity of land urbanization in the Yangtze River Delta urban agglomeration in the process of development and the availability of data, LUR was used as a dependent variable, and the population size, economic level, social basic conditions and natural environment were analyzed separately. We selected variables to build a model to explore the main influencing factors of land urbanization in the counties of the Yangtze River Delta urban agglomeration (Table 1, Figure 2). The selection of variables was mainly based on the following assumptions. ① Economic development can effectively increase the income of urban residents, improve urban living conditions and stimulate the transfer of agricultural populations to urban areas, thereby increasing the demand for urban residential, industrial, transportation and other construction land and increasing the demand for land urbanization. It leads to positive promotion [68,69]. ② Social basic conditions, the soft infrastructure of urbanization, are closely related to the lives of urban residents. Social public service mainly guides the development of urban land space by attracting the population, thereby promoting the expansion of urban residential land [48,70]. ③ Population growth in counties is the main source of demand for urban land [71,72], and the larger the population scale, the higher the level of land urbanization [49,71–73]. ④ A good natural environment should be able to better meet the expansion needs of urban construction land and contribute to the process of land urbanization [74,75]. Due to the stability of the model and the difficulty of data collection, the year 2020, with better timeliness, was used to study the influencing factors of land urbanization.

Table 1. Indicators to analyze the driving factors of LUR.

Type	Symbol	Variable	Definition
Economy	X1	Per capita GDP	Gross domestic production (GDP)/permanent population
	X2	Proportion of secondary and tertiary industry in GDP	The proportional relationship to indicate the industrial structure of a region
	X3	Fiscal revenue	Budget revenue/GDP
Social basic conditions	X4	Number of healthcare beds	An indicator to indicate the medical level of a region
	X5	Density of roads	Total road mileage/area of district or county
Population	X6	Population density	Permanent population/area of district or county
Natural environment	X7	Topographic relief	Stemming from Feng et al. [76]
	X8	Annual precipitation	In this study, it was believed that the higher the annual average precipitation, the better the natural environment

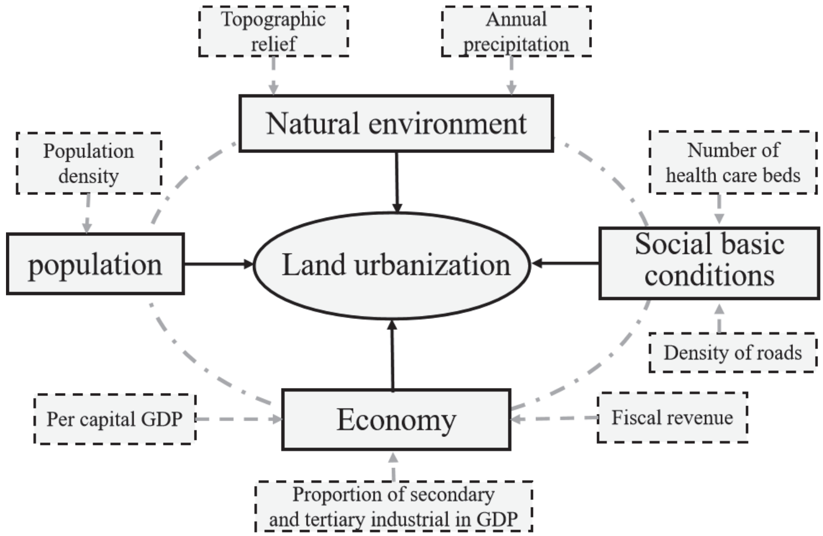

Figure 2. Analysis framework of land urbanization in Yangtze River Delta urban agglomeration.

All independent variables were standardized and tested for multicollinearity using the variance inflation factor (VIF) before running the MGWR model. The larger the VIF value, the greater the multicollinearity [77]. It is generally believed that if the VIF value is greater than 7.5 or the tolerance (the reciprocal of VIF) is closer to 0, it indicates that the multicollinearity is stronger. The VIF value of each index was less than 7.5 (Table 2), indicating no multicollinearity problem among the selected indexes.

Table 2. Influencing factors multicollinearity test.

Variable	X1	X2	X3	X4	X5	X6	X7	X8
VIF	4.776	1.892	2.552	1.704	4.210	4.817	1.110	1.189
Tolerance	0.209	0.529	0.392	0.587	0.238	0.208	0.901	0.841

The greatest difference between the MGWR model and the classical GWR model is the heterogeneity of bandwidth. This improvement is achieved by redefining GWR as in the definition of the generalized additive model (GAM) [78]. Compared with the GWR model, the MGWR model allows each variable to have different spatial smoothing levels. This model is expressed as follows:

$$y_i = \beta_0(u_i, v_i) + \sum_{j=1}^{n} \beta_{bwj}(u_i, v_i)x_{ij} + \varepsilon_i \tag{2}$$

where y_i is the LUR of i county, x_{ij} is the nth predictor variable, β_{bwj} is the optimal bandwidth used by the nth variable regression coefficient, (u_i, v_i) is the geographic coordinate of the ith spatial unit centroid, $\beta_0(u_i, v_i)$ is the intercept of the model at i, $\beta_j(u_i, v_i)$ is the regression coefficient corresponding to the jth variable of the i space unit, ε_i is the random error term and k is the number of units. The kernel function and bandwidth selection criteria of the MGWR model use the Gaussian function and AICc, respectively, and GAM uses a backward-fitting algorithm to fit each smooth term. We used SOC-f [79] as a convergence criterion with a convergence threshold of 1×10^{-5}.

3. Spatial and Temporal Evolution Pattern of Land Urbanization in Yangtze River Delta Urban Agglomeration

3.1. Land Urbanization Pattern of Yangtze River Delta Urban Agglomeration in 2010

In 2010, the land urbanization rate of the Yangtze River Delta urban agglomeration was 50.49%. According to the stage characteristics of population urbanization and the comprehensive measurement results of China's urbanization level [80–82], the land urbanization level can be divided into five types: low ($\leq$0.1), medium low (0.1~0.3), medium (0.3~0.5), medium high (0.5~0.7) and high (>0.7). As shown in Figure 3, most of the counties in the Yangtze River Delta had a land urbanization level of medium or above, accounting for about 76.19%. Specifically, among the 126 counties in the Yangtze River Delta urban agglomeration, less than 20% had a land urbanization rate greater than 0.7; however, there were medium-low-level and low-level counties, accounting for 20.64% and 3.17%, respectively. The counties with a high land urbanization level were mainly distributed in Zhejiang Province and Jiangsu Province, while the land urbanization rate of most counties in Anhui Province was relatively low, showing a pattern of high in the southeast and low in the northwest. Using the spatial analysis module in ArcGIS Pro 2.8 software, the Moran's I index of the land urbanization rate of the Yangtze River Delta urban agglomeration was calculated to be 0.579, and the z-score was 9.95, $p < 0.01$. After passing the significance test, the hot spot analysis tool was further used to analyze the cold and hot spots of the land urbanization of the Yangtze River Delta urban agglomeration. It showed that the land urbanization of the Yangtze River Delta urban agglomeration presented a significant positive spatial correlation feature, and the hot spots were concentrated in the Shanghai metropolitan area. The areas near Hangzhou, Jinhua and Wenzhou had a high land urbanization level and were surrounded by counties with a high land urbanization level. The cold spot areas were concentrated in Hefei, Chuzhou, Wuhu, Tongling, Chizhou and other cities in Anhui Province. These areas had a relatively low land urbanization level and were surrounded by counties with a low land urbanization level.

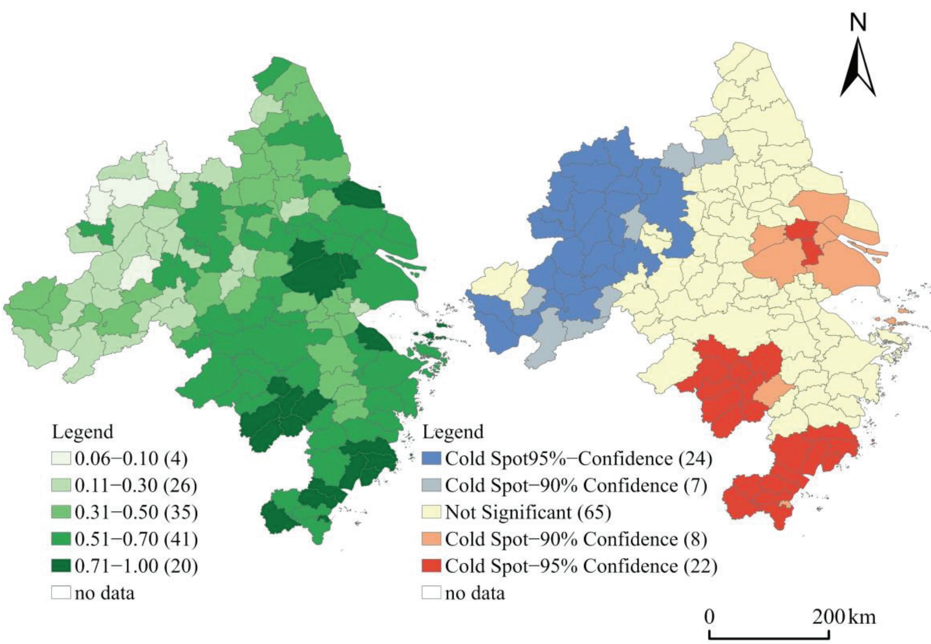

Figure 3. Analysis of land urbanization pattern and hot spots in Yangtze River Delta urban agglomeration in 2010.

3.2. Land Urbanization Pattern of Yangtze River Delta Urban Agglomeration in 2020

In 2020, the land urbanization rate of the Yangtze River Delta urban agglomeration was 55.41%. In 2020, the number of counties with a low or medium low level of land urbanization was reduced from 30 in 2010 to 25; however, the number of counties with a medium or above level reached 81.16%, and those with a land urbanization rate greater than 0.7 accounted for more than 1/4, an increase of 60% compared with 2010 (Figure 4). With the further acceleration of population urbanization, the level of land urbanization also increased correspondingly. Most of the counties in Zhejiang Province and the counties in the south of Jiangsu Province were still high-level areas. The level of land urbanization in some counties in Anhui Province increased significantly, such as in Feixi County, Lujiang County, Anqing City, Chizhou City, Dangtu County and other counties. During this period, for the development of the Yangtze River Delta region, the state proposed a new-type urbanization strategy and regional integration strategy of "coordinating urban and rural development, actively and steadily promoting urbanization", which narrowed the difference in the level of land urbanization between counties to a certain extent. The coefficient of variation for the land urbanization rate dropped from 0.458 in 2010 to 0.423 in 2020. In 2020, Moran's I index was 0.602, and the z-score was 10.32, $p < 0.01$. After passing the significance test and further using the hot spot analysis tool, it was found that the positive spatial correlation characteristics of the urbanization rate of the counties in the Yangtze River Delta urban agglomeration had improved, and the hot spots had further expanded and connected in the southwest of Zhejiang Province; it is worth noting that the hot spots near the Shanghai metropolitan area had reduced, indicating that the land development in this area had gradually become saturated; the number of counties in the cold spot area was reduced from 31 in 2010 to 27 in 2020. The cold spot area in Anhui Province shrank slightly, while Binhai County and Funing County in the north of Jiangsu Province were transformed into cold spots, indicating that the land urbanization rate of these two counties and surrounding counties was growing slowly, lagging behind the land structure adjustment in other regions.

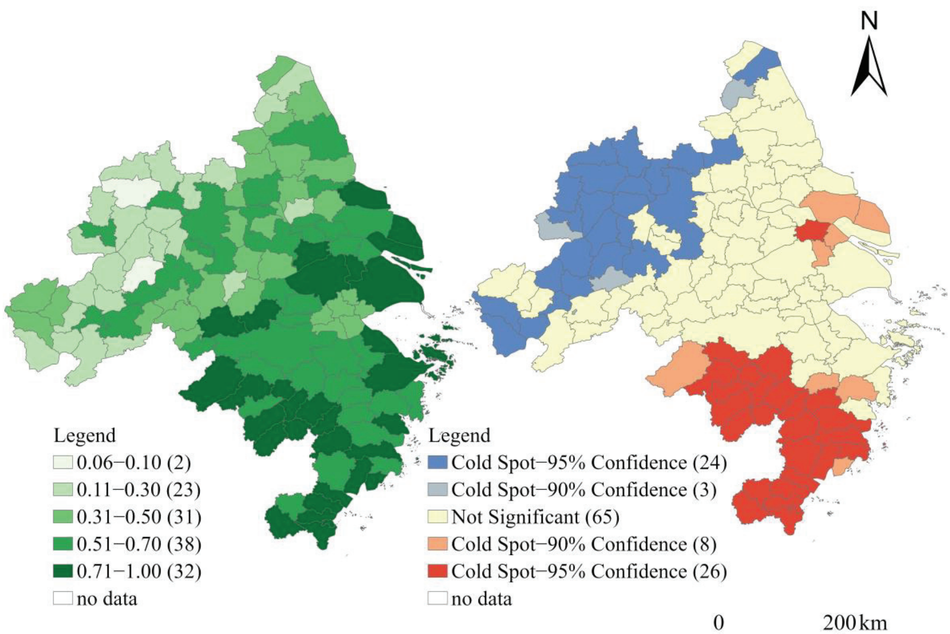

Figure 4. Analysis of land urbanization pattern and hot spots in Yangtze River Delta urban agglomeration in 2020.

3.3. Evolution of Land Urbanization Pattern in Yangtze River Delta Urban Agglomeration

3.3.1. Time Evolution Characteristics

From 2010 to 2020, the overall land urbanization rate of the Yangtze River Delta urban agglomeration increased from 50.49% to 55.41%, with an average annual growth rate of 0.50%. In developed areas, land development takes place earlier than in other, less developed areas, and the potential space for land expansion is limited. Figure 5 is a graph of the urbanization kernel density curve of the Yangtze River Delta urban agglomeration created using the Stata 15 software in order to describe the temporal evolution characteristics of the land urbanization of the Yangtze River Delta urban agglomeration. From the change of the nuclear density curve position, the curve position as a whole shows a trend of rightward migration. From the change of the peak height of the main peak of the curve, it gradually evolves from the broad peak shape to the peak shape; according to the change in the number of peaks in the curve, there is a transition from one main peak and one secondary peak on the left side to a single main peak; according to the curve tailing change, the tailing on the left side and the right side is shortened and raised. A series of changes in the nuclear density curve show that the urbanization rate of urban agglomeration in the Yangtze River Delta showed a continuous upward evolution during the study period; the difference in the level of land urbanization between counties showed a narrowing trend, and the polarization characteristics were weakening. On the whole, the land urbanization rate among the counties of the Yangtze River Delta urban agglomeration was characterized by dynamic convergence.

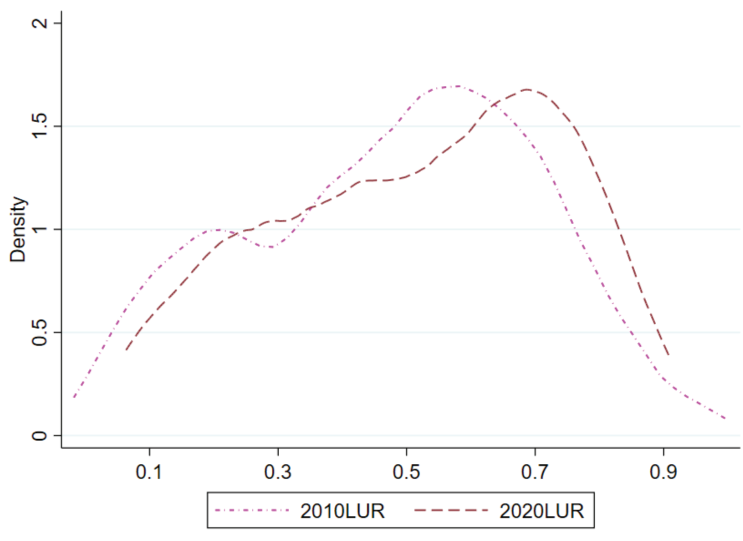

Figure 5. Estimation curve of land urbanization kernel density in Yangtze River Delta urban agglomeration from 2010 to 2020.

3.3.2. Spatial Evolution Characteristics

Referring to the average annual growth of the land urbanization rate in the overall urban agglomeration in the Yangtze River Delta, the growth in the counties was in the range of ≤0, 0~0.5%, 0.5%~1%, 1~2% and >2%. It was divided into five levels of negative growth, low speed, medium speed, high speed and ultra-high speed, and we carried out spatial statistics and Kriging interpolation simulation (Figure 6). The results showed that 64.28% of the counties had an average annual growth rate of land urbanization below 0.5%, which was lower than the regional average growth rate. Among them, the average annual growth rate of 17.46% of the counties was negative. These counties were mainly distributed in Jiangsu Province, and a small number were distributed in the coastal areas of

Zhejiang Province, such as Yuhuan City, Wenling City, etc. The average annual growth rate of land urbanization was between 0.5% and 1% in 18.42% of counties, while only 11.11% of counties had an average annual growth rate of >1%. From the perspective of provincial divisions, the land urbanization rate of counties in Zhejiang Province grew the fastest, with 22 counties with a medium speed and above, followed by Anhui Province, with 20 counties with a medium speed of growth and above. The land urbanization rate of counties in Jiangsu Province grew the slowest, and there were only two counties with a medium speed and above, indicating that the land urbanization in Anhui and Zhejiang Provinces had great potential for development. Specifically, most counties in Anhui Province with a low level of land urbanization grew faster during the study period; Shanghai and the counties near Taizhou City in Zhejiang Province also grew faster, and most of the counties in Jiangsu Province and the counties in the southeast coastal areas of Zhejiang Province had a low average annual growth rate of land urbanization.

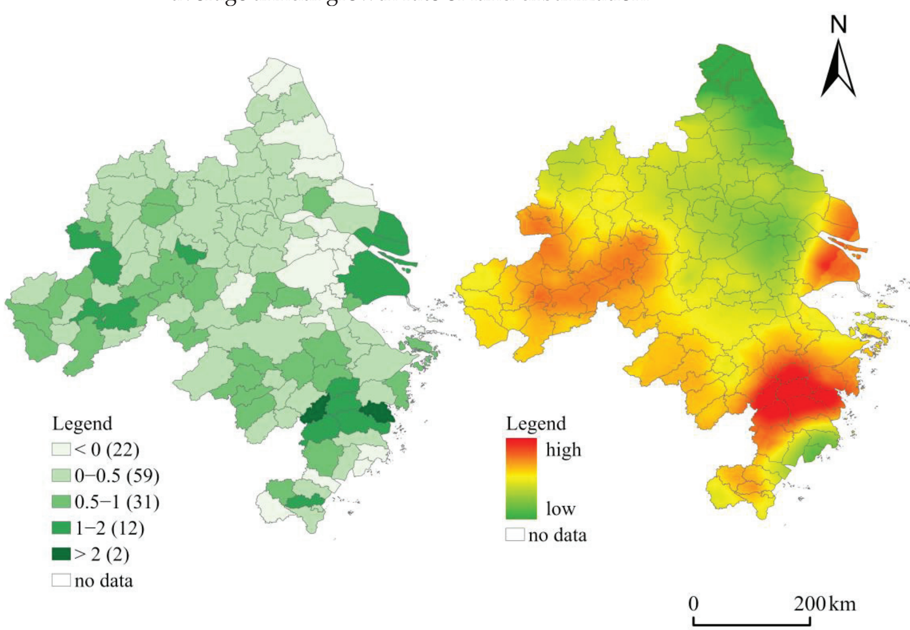

Figure 6. Change in land urbanization growth rate in Yangtze River Delta urban agglomeration from 2010 to 2020.

4. Influencing Factors of Land Urbanization in the Yangtze River Delta Urban Agglomeration

4.1. Identification of Influencing Factors and the Comparative Analysis of Models

The spatial autocorrelation analysis showed that the land urbanization levels of the counties of the Yangtze River Delta urban agglomeration were not randomly distributed in space but had significant spatial agglomeration characteristics. Therefore, a regression model with spatial effects was used, and the factors affecting land urbanization had different scales in the spatial process. Therefore, this paper used the MGWR model to explore the driving mechanism of land urbanization in the Yangtze River Delta urban agglomeration. The OLS, GWR and MGWR models were used to perform regression analysis on the influencing factors of the land urbanization level of the Yangtze River Delta urban agglomeration. Table 3 shows that the correction coefficient of determination of the MGWR model was higher than that of the OLS and GWR models, and the AICc value and the residual sum of squares were both obviously smaller than those of the GWR and OLS models. The standardized residuals calculated by the MGWR model were tested by

Moran's I and were randomly distributed in the study area, which further indicates that the MGWR model had a better fitting effect. The local R^2 calculated by the MGWR model represented the actual explanatory power of the selected variables in different spaces. The natural fracture method in the ArcGIS Pro 2.8 software was used to classify and visualize the local R^2 (Figure 7). It was found that the goodness of fit was satisfactory. There was an obvious clustering trend, and the local R^2 increased from southeast to northwest in general; all of the values were greater than 0.58, and the fitting effect was good. It can be seen that the eight variables selected in the study had specific explanatory power for the spatial pattern of land urbanization in the Yangtze River Delta urban agglomeration without considering the interference of other factors. In addition to the influencing factors selected in this paper, it also included technological innovation, social culture, policy background, etc. Limited by the difficulty of data acquisition and the model stability, these were not explored in this paper. Because of the different selection of indicators, the conclusions are different.

Table 3. Comparison of OLS, GWR and MGWR fitting results.

Model	OLS	GWR	MGWR
AICc	256.327	226.605	199.571
Adjusted R^2	0.598	0.757	0.801
Residual sum of squares	47.410	0.880	19.508
Moran's I for residual	0.208 ($p < 0.01$)	0.138 ($p < 0.05$)	0.088 ($p > 0.1$)

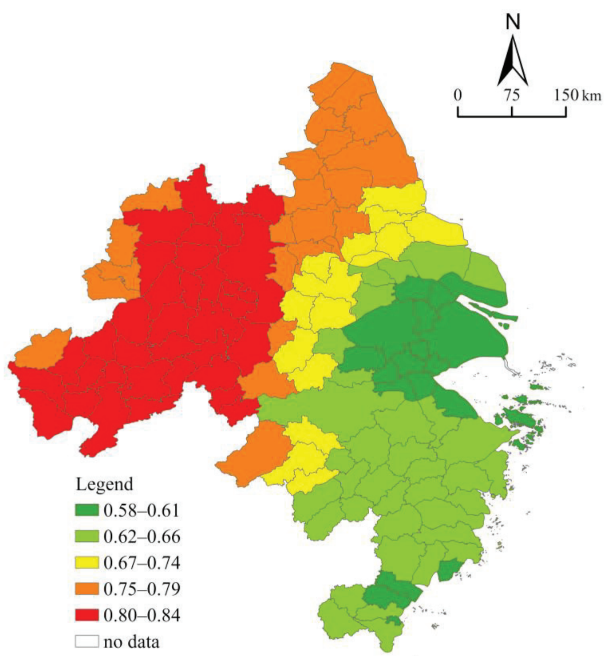

Figure 7. Local R^2 of MGWR model fitting results.

4.2. Scale Analysis of Influencing Factors Based on the MGWR Model

The variable bandwidth calculated in the MGWR model measured the spatial scale of each variable [83], which reflected the difference in the scale of land urbanization in the Yangtze River Delta urban agglomeration caused by different influencing factors. The larger the bandwidth, the larger the effect of the factor on the urbanization of the Yangtze River Delta urban agglomeration, and the smaller the spatial heterogeneity. From Table 4, it can be seen that the bandwidth of each variable in the GWR model was 78, and the optimal bandwidth of each variable was found to be different through the MGWR model. Among them, the proportions of secondary and tertiary industries, density of roads, topographic relief and annual precipitation were 122, 125, 125 and 120, respectively, which are close to the total number of counties and are global variables. In addition, the regression coefficient was relatively more stable in space. The bandwidths of per capita GDP and number of healthcare beds in medical institutions were 95 and 82, respectively, and the regression coefficient varied greatly in space. The bandwidth of fiscal revenue and population density was 43, and the effect scale was the smallest, indicating that land urbanization in the Yangtze River Delta urban agglomeration had a significant impact on fiscal revenue and population density. Moreover, the regression coefficients of these two factors varied the most in space, indicating higher sensitivity.

Table 4. Bandwidth comparison between GWR and MGWR.

Variables	Bandwidth of GWR Model	Bandwidth of MGWR Model
Intercept	78	43
X1	78	95
X2	78	122
X3	78	43
X4	78	82
X5	78	125
X6	78	43
X7	78	125
X8	78	120

4.3. Regression Coefficient Analysis of Influencing Factors Based on the MGWR Model

We used the ArcGIS Pro 2.8 software to display the regression coefficients of each variable calculated by the MGWR model (Figure 8). From the median of the regression coefficients of the influencing factors, per capita GDP > fiscal revenue > density of roads > annual precipitation > population density > number of healthcare beds > topographic relief > proportion of secondary and tertiary industries in GDP, in which the regression coefficients of per capita GDP, fiscal revenue, population density and annual precipitation were all positive values, the regression coefficient of population density was mainly positive and the positive and negative regression coefficients of number of healthcare beds accounted for half, respectively; the regression coefficient of topographic relief was mainly negative, and the regression coefficient of the proportion of secondary and tertiary industries to GDP was negative.

The standardized residual classification standard and natural breakpoint method were used to visually express the regression coefficients of the standardized residual and variables, respectively (Figure 9). The results showed that the range of the standardized residual values was −2.5 to 2.5, and the local regression models of all counties passed the residual test (Figure 9a). From the spatial distribution of the regression coefficient of the influencing factors, the influence degree of the eight independent variables on the land urbanization level of the Yangtze River Delta urban agglomeration showed obvious spatial differences (Figure 9a–i). Among the influencing factors with positive regression coefficients, the per capita GDP, road network density and precipitation showed a pattern of increasing from southeast to northwest, indicating that these three factors had a significant impact on the southeast area of the Yangtze River Delta urban agglomeration. This is because the southeast county of the Yangtze River Delta urban agglomeration was relatively developed, and the land development was early and had superior natural conditions and infrastructure construction level, while the northwest county was relatively backward; therefore, these factors were more likely to promote the urbanization level of the relatively backward counties in the northwest. The proportion of fiscal revenue to GDP was high in the middle and low in the east and west. Moreover, high-value areas were mainly distributed in the vicinity of provincial capital cities and large cities, such as Nanjing, Hangzhou, Hefei, Shanghai and other cities. The general fiscal revenue of the government was closely related to the government's regulation and control ability, which indirectly indicated that cities with high administrative levels play a stronger role in promoting land urbanization. Under China's land use right system, land supply is a powerful tool to intervene in the land market. Land finance is the main source of government financial revenue. The government's revenue from land leasing and land development accounts for a large part of the financial revenue. The macro-control ability of urban governments with high administrative levels is more prominent and has a greater impact on the development of land urbanization; the influence of population density showed that the northern region was larger than the southern region, and the high-value regions were concentrated along the Yangtze River Basin, indicating that the population agglomeration effect of the economic belt along the Yangtze River had an obvious role in promoting land urbanization, and the population scale growth is still the leading factor in promoting the development of land urbanization in developed counties. Only the proportion of secondary and tertiary industries in GDP was negatively affected by the regression coefficient, showing a spatial pattern in which the negative effect on land urbanization in the Yangtze River Delta was weakening from southeast to northwest. This is because, with the increase of the proportion of secondary and tertiary industries, the industrial structure was transformed into non-agricultural and advanced, and the development of service-oriented industries and the improvement of industrial intensification level promoted the improvement of land use efficiency, thus reducing the external expansion of land; however, due to the better industrial base in the southeast region, the effect of industrial structure improvement was better than that in the northwest region. The number of medical beds and the topographic relief had a negative effect on the developed counties in the east and a positive effect on the less developed counties in the west, indicating that these two factors are more conducive to the improvement of the land urbanization level of the less developed counties. This is because the land development degree of the western counties was relatively low, and good natural conditions and perfect public facilities configuration have a certain role in promoting land development; however, the more developed counties in the east shifted from the external expansion of the city to internal renovation and transformation due to the early land development and economic development, and their dependence on natural conditions and public facilities was further weakened.

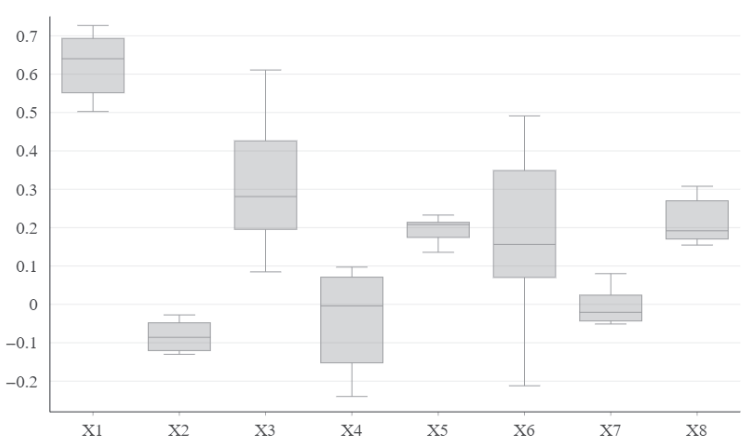

Figure 8. Regression coefficient and significance of spatial distribution of influencing factors of county economic development in Jiangsu Province.

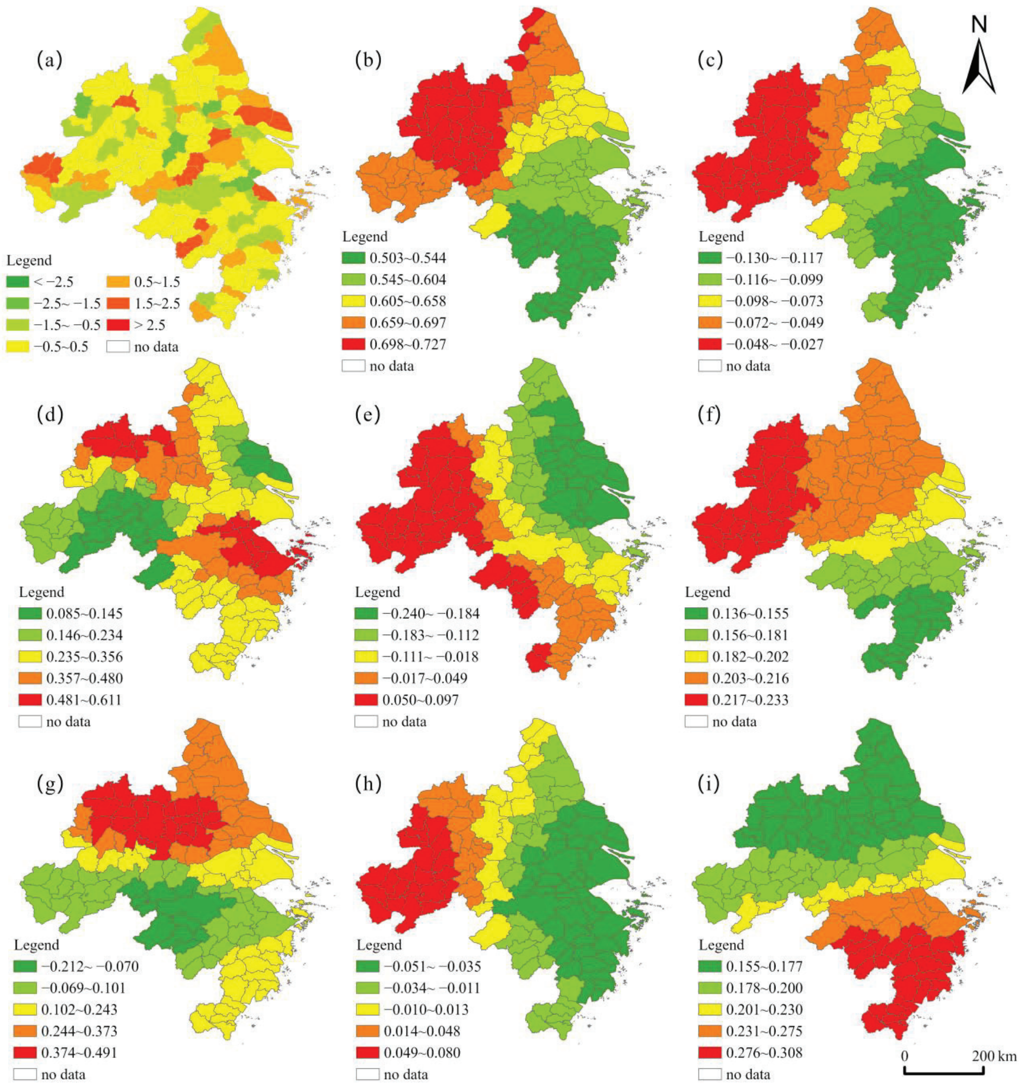

Figure 9. Spatial distribution of standardized residual and regression coefficients of driving factors for LUR based on the MGWR model in the Yangtze River Delta urban agglomeration in 2020. (**a**) Standardized residual; (**b**) per capita GDP; (**c**) proportion of secondary industry in GDP; (**d**) fiscal revenue; (**e**) number of healthcare beds; (**f**) density of roads; (**g**) population density; (**h**) topographic relief; (**i**) annual precipitation.

5. Discussion

5.1. Research Significance

In previous studies, the ratio of urban construction land to total urban area was mostly selected to reflect the urbanization level of urban land. This method is limited by the urban administrative area and cannot reflect changes in urban land use structure. Differing from previous studies, the land urbanization measurement index selected in this study corresponds to the urbanization of the population in a spatial entity through the ratio of urban construction land to urban and rural construction land and reflects the changes in land use in the urbanization process. The Yangtze River Delta urban agglomeration is an important engine for China's economic development and an important platform for its participation in international competition. The urbanization of land has reached a relatively high level, and the growth has been relatively slow in the past ten years. The difference in the level of land urbanization between counties has shown a dynamic convergence. Due to the implementation of the strategies of regional integration and new urbanization in the Yangtze River Delta, the developed counties and regions in the east have been transformed from the incremental expansion stage to the stage of stock renewal. Therefore, these regions need to pursue the improvement of the quality of land urbanization and the high-quality development of urbanization. However, the less developed counties and regions in the west and the counties and regions in the south that are greatly affected by the terrain have a high demand for urban construction land and are still in the stage of rapid improvement of land urbanization; such areas need to avoid the negative effects (such as the imbalance between population urbanization and land urbanization) caused by the rapid expansion of construction land. In the process of promoting urban–rural integration and performing spatial planning of national land, it is necessary to comprehensively consider the differences in the level of land urbanization in different counties. Previous studies have insufficiently explored the influencing factors of land urbanization in urban agglomerations, and the methods used have been relatively simple. The influencing factors are not only different in terms of influence intensity, but also different in spatial scale. The MGWR model used in this paper revealed the difference in the impact intensity and impact scale of different variables on land urbanization. The research results showed that the MGWR model yielded a great improvement in the goodness of fit compared with the GWR and OLS models, and the regression results were more reliable. This provides a theoretical and empirical basis for the further application of the MGWR model in land urbanization.

5.2. Policy Implications

Combined with the spatial and temporal evolution characteristics of land urbanization in the Yangtze River Delta urban agglomeration, we found that the speed of land urbanization in most counties slowed down, and many counties even had negative growth. This shows that, as one of the most economically developed areas in China, the level of land urbanization has entered a mature stage. Against the current background of promoting the urbanization construction with the county as an important carrier, it is particularly important to improve the development level of land urbanization and its coordination with population urbanization in the Yangtze River Delta urban agglomeration. We found that economic development is the main factor in promoting the land urbanization of the Yangtze River Delta urban agglomeration. The macro control of the government also plays a very important role in the process of land urbanization. The higher the administrative level, the stronger the macro-control role of the urban government. Under the land use right system of China, land supply is a powerful tool with which the government can intervene in the land market; the income from land supply contributes greatly to local income and infrastructure construction [84]. In response to the development trend of land urbanization and the challenges of sustainable development in the Yangtze River Delta urban agglomeration, we put forward some policy suggestions. ① First, the existence of regional differences in land urbanization in the Yangtze River Delta urban agglomeration determines that all counties need to be based on the regional perspective in the development and utilization of land resources. The government departments need to comprehensively consider the spatial interaction between the county and neighboring counties, strengthen the linkage control role of cities in land urbanization, continue to reduce the regional differences in land urbanization and promote the coordinated and integrated development of urban agglomeration. ② Second, we need to promote the construction of a people-oriented, new type of urbanization. In urban development, we need to promote people-oriented connotative population urbanization to replace the extensional land urbanization based on urban space expansion, strengthen the tapping of the existing land stock in developed areas led by the Shanghai metropolitan area, focus on the population growth and the improvement of social basic conditions in less developed areas in Anhui Province and promote the coordinated development of population urbanization and land urbanization. ③ Third, we should promote the transformation of kinetic energy of urban development and the transformation and upgrading of industrial structure. The analysis results show that the upgrading of industrial structure and intensive development can promote the renewal of land stock in developed counties in the east and also help to slow down the land expansion in less developed counties in the west and can strengthen the dynamic convergence trend of regional land urbanization level. ④ Fourth, according to the actual development needs of the county, we should implement the differentiated construction land allocation policy, promote the structural reform of the land supply side and release the local fiscal revenue from the real estate market [85], gradually getting rid of the dependence on land finance. The counties with lagging land urbanization should make use of the advanced management technology and development experience of the counties with a high land urbanization level in the east to avoid negative effects in the process of rapid urbanization. ⑤ Finally, it is necessary to give full play to the key role of the market and the government in resource allocation. The government's supervision of land development is aimed at avoiding the destructive impact of externality on the market operation efficiency. In the process of rationally promoting land urbanization, it is necessary to comprehensively consider the coordination and unification of economic benefits, social benefits, ecological benefits and urban space carrying capacity [86] and promote new-type urbanization and rural revitalization through urban–rural integration and rural revitalization strategy.

6. Conclusions

Based on the remote sensing monitoring data of China's land use status, this study calculated the LUR of each county in the Yangtze River Delta urban agglomeration and used spatial autocorrelation and kernel density estimation curves to reveal the spatiotemporal land urbanization of 126 counties in the Yangtze River Delta urban agglomeration from 2010 to 2020. We evaluated the dynamic evolution pattern and further applied the MGWR model to explore the scale effect and spatial heterogeneity of various influencing factors. The main conclusions reached are as follows:

(1) From 2010 to 2020, the overall land urbanization rate of the Yangtze River Delta urban agglomeration increased from 50.49% to 55.41%, with an average annual growth rate of 0.50%. As the region with the most active economic development and the most concentrated cities in the country, its land urbanization gradually increased to create a saturated state. Among the counties, the average annual growth rate of nearly 64.28% lagged behind the overall growth rate, mainly distributed in Jiangsu Province and Zhejiang Province. Overall, the level of land urbanization in each county showed dynamic convergence characteristics;

(2) The differentiation pattern of land urbanization in the Yangtze River Delta urban agglomeration from southeast to northwest was more obvious. The hot spots of land urbanization were consistently mainly distributed in the Shanghai metropolitan area, Hangzhou, Jinhua, Wenzhou and nearby counties and showed a trend of diffusion. The cold spots were concentrated in Hefei, Chuzhou, Wuhu, Tongling, Chizhou and other cities, where there was a shrinking trend;

(3) Compared with the GWR model and the OLS model, the MGWR model has a better fitting effect and is better suited to the study of the influencing factors of land urbanization. On the impact scale, the proportion of secondary and tertiary industries in GDP, density of roads, topographic relief and annual precipitation have larger bandwidths, which are close to global variables, while fiscal revenue and population density have the smallest bandwidths and the strongest spatial heterogeneity. In terms of impact intensity, economic factors have the greatest impact, while natural environment factors have the least impact.

Our empirical research revealed the spatiotemporal dynamics of land urbanization in the Yangtze River Delta urban agglomeration and verified the spatiotemporal heterogeneity effects of the economy, social basic conditions, population and natural environment. These findings are helpful for formulating urban and regional planning for specific regions with different spatial dependencies and the co-evolution of urban expansion. The spatial difference in land urbanization is the result of a combination of factors. In future research, we will compare and analyze the spatiotemporal evolution and driving factors of land urbanization in other urban agglomerations.

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Evolutionary Logic and Development Foresight of Environmental Collaborative Governance Policy in the Yangtze River Delta

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Abstract: The experience of environmental governance in the Yangtze River Delta has formed the practical paths of cross-administrative cooperation and eco-civilization adaptation to economic development. As a result of a scientific analysis of policy texts on collaborative environmental governance in this region, this paper explores differences and core concerns, uncovering the development vein and mapping out the internal logic in order to provide a reference example for multi-regional governance. The policy has shifted from decentralization to authority, from universality to precision, from sustainable development to a community of common ecological destiny, from authoritarianism to co-governance, and from institutional norms to propaganda and guidance. Since the beginning of the new century, the internal logic of environmental governance policy in the Yangtze River Delta has been in line with the trend of coordinated development. In the future, efforts should be made to deepen the trinity mechanism of decision making, implementation, and supervision. When making decisions, we should further emphasize the unified standard of centralized environmental management and adhere to precise pollution control. Implementation will gradually establish the three-dimensional coordination mechanism of region, function, and role; supervision will involve the platform "internet + environment", and the assessment will involve "pressure mechanism + environment".

Keywords: environmental governance; collaborative governance mechanism; policy changes; Yangtze River Delta; analysis of policy text

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1. Introduction

The environment is a global issue that directly affects the achievement of global sustainable development. It is an integral aspect of the 17 ambitious Sustainable Development Goals (SDGs) of the UN [1]. Human activities and the environment are closely linked and interact in complex ways [2]. In the practice of environmental governance, it is often found that environmental problems cannot be solved in isolation, but require collaborative governance between different administrative units [3,4]. For example, in managing atmospheric environmental issues, because atmospheric pollutants can be diffused, they cannot be handled only in a small area; multi-regional collaborative management often makes pollution management twice as effective with half the effort [5].

The 2022 Chinese government work report proposes to "continuously improve the ecological environment and promote green and low-carbon development", to strengthen the comprehensive management of the ecological environment, to fight the battle against pollution, and to collaborate in order to promote high-quality economic development and health-level eco-environment protection. "Let green become the foundation of high-quality development" has become a logical starting point for the construction of an eco-civilization. Developing an ecologically safe society begins with the deepening of the institutional structure of environmental governance and the enhancement of cross-provincial and municipal collaborative governance. The Yangtze River Delta region (YRD) is an international pioneer in the collaborative governance of environmental regions, continuously introducing and implementing a series of proactive policies from the top down, integrating cross-domain administration technology capital, talent, and other resources, and improving the governance capacity for collective prevention and control, which together create the "Yangtze River Delta environmental governance experience".

Currently, the research in the cross-domain field of environmental collaborative governance mainly focuses on four aspects. Physical theory and experimental methods are employed to analyze the reasons for the difficulty in controlling environmental pollution in the YRD. Researchers have discovered the sources of pollution and transport processes [6] through a comparative analysis of the YRD and other key development areas [7,8] and have presented their findings: the YRD urban agglomeration is still in the running-in phase, but it has removed the low-level coupling relationship and achieved green development [9]. Second, researchers have focused on a single subject, such as energy in the YRD [10], green space [11], land-use efficiency [12,13], air emissions [14,15], etc., exploring the optimal governance path for environmental problems in the YRD. Third, researchers have paid attention to the effectiveness of the policy itself. Legislative cooperation in the YRD is still in its exploratory phase. The logical compatibility of the current legal system needs to be strengthened, and there is still room for improvement in the operational effectiveness of legislative cooperation [16]. From the perspective of law enforcement, the role of a fair competition review in breaking local protections, regional blockades, and industry barriers should be highlighted. An integrated or coordinated competition law enforcement system and mechanism in the YRD should be reasonably constructed [17]. Fourth, studies have focused on evaluating policy diffusion models and implementation effects, on conducting in-depth research on reproducibility, policy effect characteristics, and differences in regulatory objects under different policy diffusion models [18], and on predicting the future trend of green development efficiency in the YRD [19]. The above research results have laid a specific research foundation for this paper, but there are also some shortcomings. First of all, few works in the literature have taken the YRD's environmental collaborative governance policy as the research context. This makes it difficult to analyze how three provinces and one city make use of policy formulation to solve the problem of collaborative governance at a deep level. Secondly, regarding research methods, there is a lack of comprehensive and in-depth analyses of environmental policies in the YRD, and policy recommendations based on the description of the current situation lack scientificity and feasibility. Lastly, based on the research conclusions, most studies have focused on optimizing environmental governance. They lack a future vision and are unable to form innovative governance strategies.

In the practice of regional collaborative governance, local governments often rely on top-down policies as a driving force. Many obstacles have prevented policy implementation, such as the diversity and independence of different regional policy-making bodies and the regional competition for policy-generated benefits [20]. In addition to exploring a standard code of conduct for integration, the YRD works to coordinate regional development among various administrative units. Firstly, rapid economic development makes it difficult to maintain a balanced ecosystem. There is a growing contradiction between economic development, population growth, environmental degradation, and resource depletion in the YRD. In economically developed regions, how can we ensure the regular operation of the ecosystem? How can ecological balance be maintained? Environmental governance has become a significant concern in key regions. Secondly, many environmental governance guidelines make it challenging to control cross-domain pollution. Environmental pollution in the atmosphere, watersheds, oceans, and soils is diffuse and permeable, has cross-regional effects in the YRD, and is poorly reversible and influential. It is difficult to achieve the expected governance effect by depending on any single local governance action. Finally, different governance standards make it difficult to unify the implementation efforts. The YRD has not yet formed a unified collaborative governance institution or organization. Fundamentally resolving the problem of pollution transfer caused by different environmental standards is challenging. To improve the quality and efficiency of regional pollution control, it is necessary to focus on the following areas: the evolution of regional environmental governance policy, the evaluation period of the provincial environmental collaborative governance policy, and the future interests of regional environmental collaborative governance policy.

2. Materials and Methods

2.1. Study Area

According to the *Outline of the Yangtze River Delta Regional Integration Development Plan* issued by the *State Council* in 2019, the YRD includes 41 cities in Shanghai, Jiangsu Province, Zhejiang Province, and Anhui Province, with a total area of 358,000 km^2 (Figure 1). With less than 4% of the national land area, it produces nearly 1/4 of the total economic output and holds nearly 1/7 of the entire population. It is one of the regions with the most active industrial development, the highest degree of openness, and the most robust innovation ability in China. However, economic and population accumulation leads to the rapid consumption of resources and the aggravation of environmental pollution [21]. This includes severe soil pollution, the shortage of water resources, and the aggravation of air pollution. The complex socio-economic and social-ecological environments have increased the difficulty in the collaborative environmental governance of the YRD. It is necessary to deepen the construction of institutional environmental governance in various provinces and cities as this will promote the sustainable development of the ecology and the economy in the YRD.

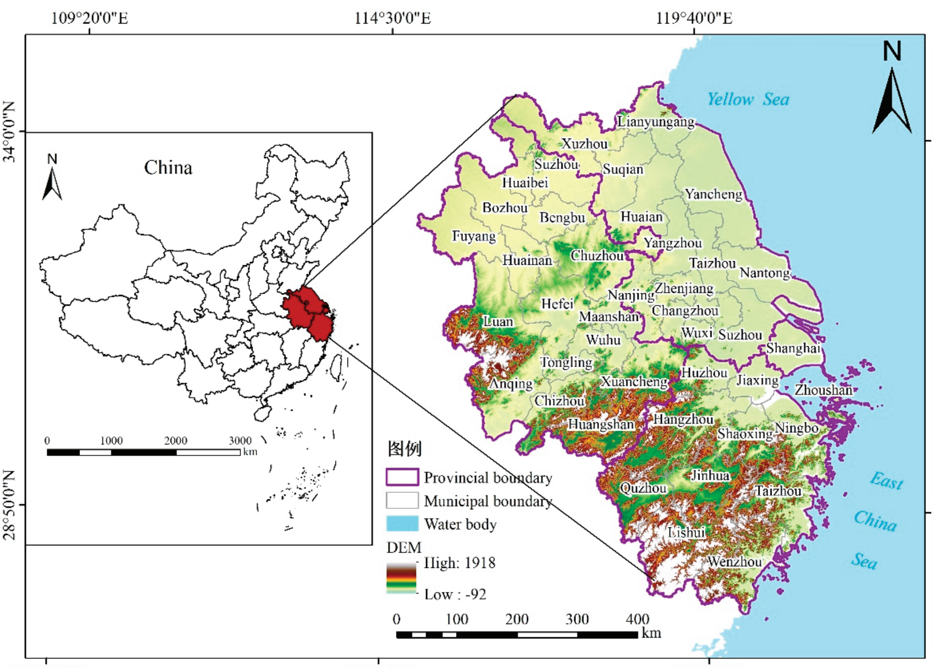

Figure 1. The map of the Yangtze River Delta region (YRD).

2.2. Study Methods

The research design is the embodiment of the overall framework. In order to systematically analyze the logic of policy evolution in the collaborative environmental governance of the YRD, this paper focuses on the relevant policies at the central level. These policies involve environmental issues in the YRD. The collaborative governance policy text is used as the basic data, and the Nvivo12 software is used as a coding tool for in-depth exploration. After data retrieval and review, a total of 42 State Council documents, 32 Zhejiang documents, 54 Jiangsu documents, 41 Anhui documents, and 14 Shanghai documents were screened, totaling 183 documents.

Following the principles of openness and authority, we adopted the research method of policy text analysis, focused on the theme of "Yangtze River Delta Environmental Governance", used "Yangtze River Delta", "integration", "environmental governance", "energy saving and emission reduction", and "ecological environment" as keywords, and scanned and collected relevant government documents published on the government affairs public website, including those issued by the *Central Committee of the CPC*, the *State Council*, the *Ministry of Ecology and Environment*, the *Department of Ecology and Environment of Zhejiang Province*, the *Department of Ecology and Environment of Jiangsu Province*, the *Department of Ecology and Environment of Anhui Province*, and the *Shanghai Municipal Bureau of Ecology and Environment*, which are all relevant policy documents for the extraction of effective policy signals. The 183 policy documents were chosen based on the fundamental research dimensions of role object, topic orientation, policy means, functional orientation, and action mode to form a complete coding system (Figure 2), which were used to compare the coordination of environmental collaborative governance policy design in various regions. Schemes and differences were identified, and the typical characteristics of the experience of collaborative environmental governance in the YRD were explored.

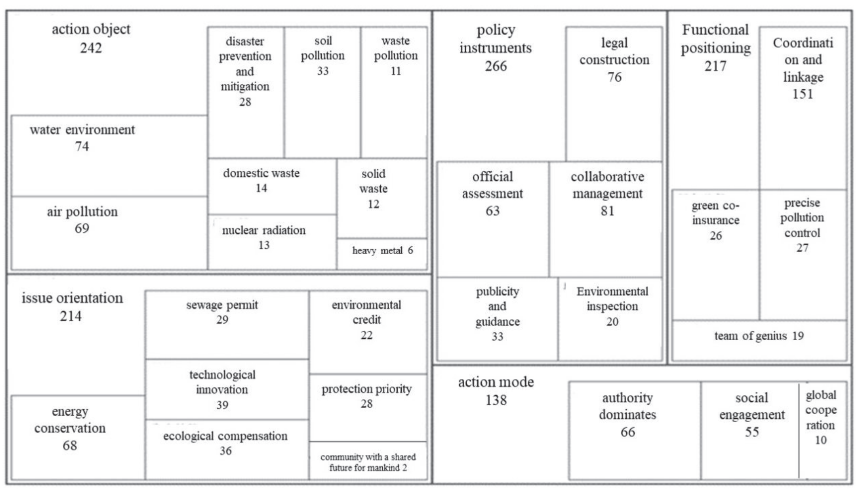

Figure 2. Node coding level and the set of reference points.

2.3. Study Tools

Policy text analysis is a content research method that combines qualitative and quantitative methods. Nvivo12, developed by the QR company, is used as a coding tool to mine information about materials [22]. It also directly reflects the environmental collaboration preference of each province and city. We imported 183 policy texts into Nvivo12 for open coding (establishing free nodes), spindle coding (establishing tree nodes), and selective coding. Finally, 28 core nodes were formed with 1120 reference points, as shown in Table 1.

Table 1. Coding of policy texts at various government levels in the Yangtze River Delta.

	Government Level	Number of Policy Documents	Typical Policy Text	Number of Coding Reference Points
Central level	The *State Council*	42	*Outline of the Yangtze River Delta integrated regional development plan* *The overall plan of the integrated Yangtze River Delta ecological and green development demonstration area* *Measures for the assessment of the implementation of the air pollution prevention and control action plan* *Soil pollution prevention action plan* … …	401
Provincial level	Zhejiang Province	32	*Further promoting the reform and opening up as well as economic and social development in the Yangtze River Delta region, relevant key work division plan* *Notice from the general office of the people's government of Zhejiang Province on printing and distributing the 2020 implementation plan of the "4 + 1" major project construction plan in Zhejiang Province* *Zhejiang Province's "three lines and one single" ecological environment zone management and control plan* … …	189
	Jiangsu Province	54	*Three-year construction plan for ecological environment monitoring and the monitoring system in Jiangsu Province (2018–2020)* *Implementation plan of the Jiangsu Province vessel emission control zone in Yangtze River Delta Waters* *Implementation of opinions of the general office of the provincial government on accelerating the development of green, circular, and low-carbon transportation* … …	224
	Anhui Province	41	*Anhui Province's enterprise environmental credit and green credit linkage measures (for trial implementation)* *Implementation plan for Anhui Province's three-year action plan for winning the blue sky defense war* *Anhui Province green development action implementation plan* … …	167
	Shanghai	14	*Memorandum of understanding on cooperation in implementing credit joint rewards and punishments in the field of environmental protection in the Yangtze River Delta* *Opinions on the implementation of the city's "three lines and one single" ecological environment zoning management and control* *Memorandum of work on the coordinated promotion of the integration of benchmarks for ecological and environmental administrative penalties in the Yangtze River Delta region* … …	139
Total		183	… …	1120

3. Results

3.1. Overall Overview of the Policy

From the combined comparison of the form and the specific content of the policy text on the horizontal axis, it can be seen that the text forms of the *State Council* and those of the three provinces and one city are mainly based on incentive policies such as notices and opinions, while other forms are supplemented (Figure 3). However, there are problems such as the generalization of topics. Most of the planning texts, such as the *13th Five-Year Plan for Economic and Social Development of the People's Republic of China* (from now on referred to as the *13th Five-Year Plan*) and the *14th Five-Year Plan*, mention the necessity for collaborative environmental governance in the YRD, which is relatively macro in outline form; it also lacks detailed implementation documents. Few administrative policies deal with formal and specific practical procedures, steps, and principles. For example, the *Outline of the Yangtze River Delta Regional Integrated Development Plan* clarifies the path and direction of the coordinated and integrated development of the YRD as well as the principles, policies, and action plans that must be adopted for the shared environmental governance issues.

According to the word frequency analysis of the word cloud based on 1120 coding reference points, a keyword cloud analysis diagram is formed. The word frequency data in Table 2 reflect three of the YRD environmental collaborative governance policy's apparent characteristics. The first is that the keywords "region", "integration", "Yangtze River Delta", "comprehensive governance", and "informatization" have a total of 2790-word frequencies, indicating that both the collaborative governance path and the policy measures focus on the development of the whole and the part, intentionally reducing the gap in the YRD in terms of the efficiency of ecological-environmental pollution control as well as benchmarking the development experience of the "first trial, demonstration, and leading" regions in order to increase the overall effectiveness of regional environmental governance. However, this does not mean that the governance content must be the same. While maintaining the same goals and standards, we should also respect the different government schemes and policies adapted to local conditions within the jurisdictions of the YRD. Second, keywords such as "people's government", "Ministry of Agriculture", "joint meeting", and "enterprise" have a total of 1902-word frequencies, revealing that the current environmental governance policy process is primarily controlled by the competent administrative department, with support from other groups. However, policy attention has gradually shifted to enterprises, which reflects the prominent role of enterprises in pollution discharge and pollution prevention and control. A total of 1407 words in the document are related to pollution, such as "pollution", "motor vehicles", "drinking water", "heavy metals", and "licenses", demonstrating the government's goal of precise pollution control, which begins with source prevention and management in order to improve emissions trading and ecological compensation, and to support the improvements in the cross-administrative regions' environmental pollution control systems.

Table 2. Word cloud word frequency analysis.

Words	Frequency	Words	Frequency	Words	Frequency
Region	1488	Pollutants	611	Water pollution	205
Environmentally friendly	1359	People's government	293	Pollution source	198
Monitor	1307	Motor vehicle	242	Heavy metal	192
Enterprise	1247	Integration	238	License	182
Emission	1242	Informatization	232	Ministry of Agriculture	132
Yangtze River Delta	702	Drinking water	224	Comprehensive governance	130

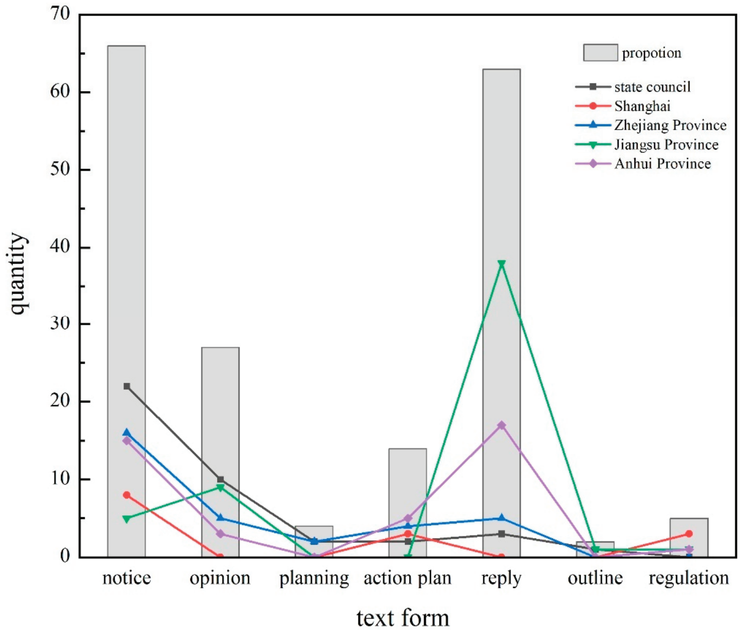

Figure 3. Statistics representing policy texts.

3.2. Evolutionary Logic of Policy Changes

During the period of the *13th Five-Year Plan*, the national strategy for the integrated development of the YRD changed from blueprint design to comprehensive construction. Due to severe pollution problems, the YRD has explored a new path of eco-priority, green, and high-quality development [23], which helps explore the "Environmental Governance Experience in the Yangtze River Delta". In June 2020, the ecological environment departments of the three provinces and one city jointly signed the *Work Memorandum on Coordinated Promotion of the Integration of the Ecological Environment Administrative Penalty and Discretion Benchmarks in the Yangtze River Delta Region*, which unifies the environmental governance standards in the YRD, formulates ecological-environmental protection plans, improves regional pollution, and accelerates the construction process of green integrated development demonstration zones, thus clarifying the implementation path for the *14th Five-Year Plan*. According to the quantitative analysis of the policy texts, the logic of the evolution of environmental policies in the YRD is mainly divided into three stages (Figure 4). As the characteristics of each stage are reflected in the policy text for the first time, the internal logic of the YRD's environmental collaborative governance experience is explored in five dimensions: change trajectory, functional positioning, issue orientation, action mode, and policy instruments.

3.2.1. Change Trajectory: From Decentralization to Authority

It can be seen from the specific content of the policy texts (from that of the *State Council* to that of the provincial governments), which deal with the collaborative environmental governance of the YRD, that the central government's form of instruction for the collaborative environmental governance of the YRD is constantly changing. From the initial decentralized and specialized opinions or notifications, it has risen to the national strategic level, subsequently formulating the outline of the development plan and enhancing the authority of the regional government's environmental collaborative governance policy.

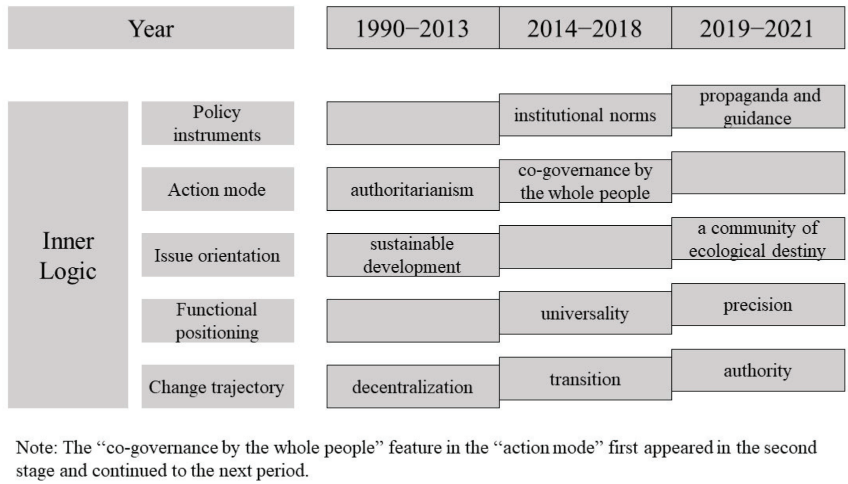

Figure 4. Inner logic diagram of policy carding.

The first phase was the period of policy dispersion, from 1990 to 2013. After the construction and opening of the *Shanghai Pudong New Area* in 1990, the idea of synergy in the YRD gradually emerged. The main objective was to integrate 16 cities in Jiangsu, Zhejiang, and Shanghai. From among a wide range of laws, regulations, and policy texts, one of the focuses in 2013 was integrated development. Furthermore, the breadth and depth of the development practice acquired for more than 20 years were still insufficient, especially regarding environmental governance in the YRD. There is a lack of authoritative guidance and development plans. Taking the *11th Five-Year Plan* issued in 2007 as an example, the *Notice of the General Office of the State Council on Printing and Distributing the National Comprehensive Disaster Reduction 11th Five-Year Plan* emphasizes the comprehensive capacity building performed in the YRD to deal with major disasters. Research has been conducted on the mechanism of disaster occurrence, the law of activities, and the relationship between secondary disasters; the *Notice of the State Council on Printing and Distributing the National Environmental Protection 11th Five-Year Plan* clarifies that it is necessary to strengthen the comprehensive improvement of the regional environment of the YRD urban agglomeration, and to focus on reducing the total emissions of major pollutants. The coordinated environmental governance policies of the YRD were incorporated into the specialized policy texts during this period. In response to the shared environmental problems that all parts of the country are facing and need to solve urgently, the central government put forward universal solutions. It also emphasized the importance of the special status of collaborative governance in the YRD, particularly in relation to environmental policy design.

The second stage is the policy transition period from 2014 to 2018. The first successful exploration of the three provinces and one city in the field of air pollution cooperation opened the stage of coordinated governance in the YRD, from decentralized exploration to authoritative recognition. Consistent with the "establishment of a regional linkage mechanism for pollution prevention and control", it is necessary to focus on ecological integrity and to break regional boundaries. A first working meeting of the *Yangtze River Delta Regional Air Pollution Prevention and Control Collaboration Group* was held in Shanghai in January 2014 under the principles of "consultation and coordination, responsibility-sharing, information sharing, and joint prevention and control" [24]. The relevant leaders of the state ministries and commissions and those of the local governments in the YRD all actively participated in realizing the organic integration of vertical and horizontal intergovernmental relations [25]; they also jointly reviewed and unanimously approved the "*Working Charter of the Air Pollution Prevention and Control Cooperation Group in the Yangtze River Delta Region*". The team fully played its coordination role and explored a practical model for the joint prevention and control of cross-regional pollution. In December 2016, the first working meeting of the *Yangtze River Delta Regional Water Pollution Prevention and Control Collaboration Group* was held in Hangzhou to clarify the goal of improving the efficiency of the operating mechanism. It aimed to be consistent with the air pollution prevention and control coordination mechanism, and to achieve institutional co-sponsorship and deliberation. Since then, joint prevention and control mechanisms have been developed, which cover air pollution, water pollution, soil pollution, energy conservation, and emission reduction in the YRD. Regulations are helpful for the construction and operation of mechanisms such as regional testing, collaborative business, and joint law enforcement supervision.

The third stage is the period of policy authoritativeness, which began in 2019. Policy guidance and support from the national level will help to overcome the shortcomings of local spontaneous cooperation, to dilute the division of administrative regions, and to gradually shift from "fragmented" to "systematic" environmental collaborative governance in the YRD [26]. In 2019, the *State Council* issued the *Outline of the Yangtze River Delta Regional Integrated Development Plan*, which proposed to vigorously develop the green economy and to achieve the internal co-governance and co-protection of ecological space. Zhejiang Province developed the *Zhejiang Province Special Action Plan for Promoting the Integrated Development of Ecological Environment Protection in the Yangtze River Delta*. In terms of jointly building an eco-civilization system, promoting the coordinated governance of rivers, lakes, and seawater environments, and strengthening cooperation in local eco-environmental protection, the YRD thus promotes the integrated development of eco-environmental protection [27]. In November 2019, the *National Development and Reform Commission* released the *Overall Plan for the Demonstration Zone of Ecological Green Integrated Development in the Yangtze River Delta* and the *Three Unification System Construction Action Plan for Ecological Environment Management in the Ecological Green Integrated Development Demonstration Zone in the Yangtze River Delta* in October 2020. These policies show the YRD's determination to take the lead in exploring regional, ecological, green integrated development. In January 2021, the *Yangtze River Delta Regional Ecological Environment Joint Protection Plan* was officially issued, marking the first time that "Yangtze River Delta Environmental Collaborative Governance" appeared in an authoritative policy document, which focused on the systemic, regional, and cross-border issues faced by the YRD. Ecological and environmental problems were also highlighted. The regional cooperation mechanism of unified planning and unified law enforcement and supervision was thus strengthened, indicating that the collaborative environmental governance of the YRD has reached a new level.

3.2.2. Functional Positioning: From Universality to Precision

The YRD prioritizes active economic development, reform, and innovation. However, the eco-environment has been overloaded for a long time. Due to the significant differences in natural resource endowments, economic and social conditions, and eco-environment governance efficiency, the causes of environmental pollution are complex. The stakeholders are diversified. It is difficult for universal policies to meet reality, and achieving the goal of eco-friendly and green integrated development is problematic. Therefore, policy functions have begun to tilt towards precise positioning, and policy documents emphasizing precise pollution control paths have become more and more abundant. Precision differs from pertinence as it emphasizes the specific analysis of specific problems and creates policy synergies in particular areas. From the Nvivo 12-encoded data (Table 3), it is apparent that the environmental protection policy in the YRD is dominated by the three significant battles of atmosphere, water, and soil, supplemented by other environmental protection fields. Government attention has constantly been extended to disaster prevention and mitigation, waste pollution, domestic waste, and nuclear radiation. Despite the vigorous implementation of collaborative governance policies, the environmental battle involves a lot of eyesight and takes a long time. To promote the optimization and upgrading of pollution prevention and control paths, it is necessary to continuously accelerate the transformation of policy function positioning from universality to precision.

Table 3. Node hierarchy and coding information with precise pollution control "objects of concern".

Node	Child Node	Reference Points	Coding Example
Object of attention	Air Pollution	79	Enhance the Meteorological Service Function of the Ecosystem in the YRD
	Water pollution	74	Strictly implement water pollution prevention and control measures
	Soil pollution	33	Classification and prevention of soil environmental pollution
	Disaster Prevention and Mitigation	28	Strengthen environmental risk prevention and emergency measures
	Domestic waste	14	Sort and dispose of municipal waste to promote reduction and harmlessness; strengthen major scientific and technological breakthroughs in pollution prevention and control
	Nuclear radiation	13	Strictly supervise the nuclear and radiation environment, and cooperate with the Public Security Department to carry out a special campaign for the safety of radioactive sources in the province
	Solid Waste	12	Promote the safe disposal of solid waste
	Heavy metal	6	Implement total emission control of key heavy metal pollutants in key areas for comprehensive prevention and control of heavy metal pollution

The reference point for "air pollution" is 79, which focuses on precise pollution control. Efforts to enhance the meteorological service function of the YRD ecosystem have achieved remarkable results. Since implementing the *State Council*'s *Air Pollution Prevention and Control Action Plan* in 2013, the YRD has actively promoted the joint prevention and control and data sharing in the YRD and has coordinated the management of air pollution in the region. In 2017, the annual average concentration of fine particulate matter in the atmosphere of 25 cities in the YRD was 44 $\mu g/cm^3$. Compared with 2013, this amount decreased by 34%. The environmental collaborative governance strategy has achieved positive results. However, in the first half of 2018, the PM2.5 concentrations in 24 cities in the YRD rebounded. Therefore, the *Notice of the Three-Year Action Plan for Winning the Blue-Sky Defense War* was issued, which adheres to problem orientation and the establishment of measures to "optimize the industrial structure and promote green development" according to local conditions. The three provinces and one city actively responded and formulated local action plans. From 2018 to 2020, the overall air quality in the YRD improved. The proportion of days with good air quality in cities has increased yearly, and the values of $PM_{2.5}$ and PM_{10} have decreased annually (Figure 5).

The "Water Pollution" reference point is 74. As the key target of the three major environmental battles, the YRD strictly implements water pollution prevention and control measures and unifies local standards. The YRD attaches high importance to rural eco-environmental protection, and thus local standards were formulated early. However, the effectiveness of rural eco-environmental protection has been hindered by objective and subjective constraints, and it is not easy to get through the last mile of phased progress. To promote the comprehensive improvement of the rural environment, the government departments of the three provinces and one city continue to identify and analyze the differences in environmental protection between the rural and urban areas; they also continue to carry out improvements in the rural living environment and establish a pollution disposal system that conforms to the actual situation in the countryside. Taking domestic sewage treatment as an example, Zhejiang Province issued the *Water Pollutant Discharge Standards for Rural Domestic Sewage Treatment Facilities* in 2015. Then, Shanghai, Anhui Province, and Jiangsu Province began to draft relevant documents on the rural domestic sewage discharge standards within their jurisdictions. The local standards for rural domestic sewage treatment in the YRD are significantly more advanced than those of the national government departments. Until August 2020, the *Ministry of Ecology and Environment* and the *Ministry of Housing and Urban-Rural Development* jointly issued the *Notice on Accelerating the Development of Local Rural Domestic Sewage Treatment and Discharge Standards*, which required localities to pay attention to the development progress of rural domestic sewage treatment and discharge standards, thereby improving the level of rural domestic sewage treatment (See Table 4).

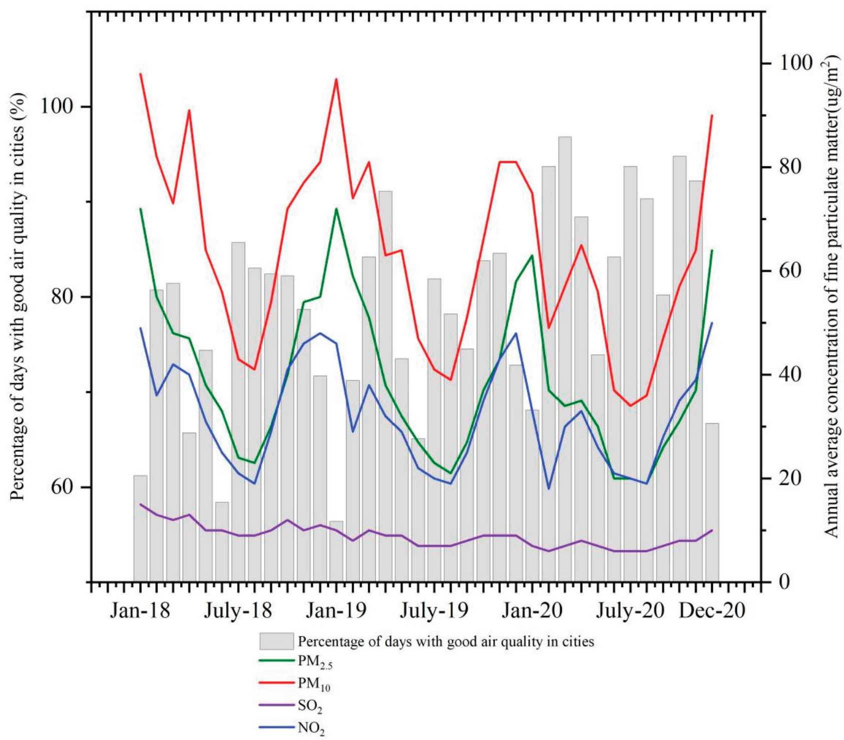

Figure 5. Trend chart of air quality change in the YRD.

3.2.3. Issue Orientation: From Sustainable Development to a Community of Common Ecological Destiny

Issue orientation was originally an environmental protection concept that was passed down from generation to generation under sustainable development. International cooperation and environmental protection policies were then extended to encompass the vision of a community with a shared future for humanity (Table 5). *China's 21st Century Population, Resources, Environment, and Development White Paper* in 1992, for the first time, revealed that the sustainable development strategy was incorporated into the long-term planning of national social development, emphasizing the appropriate development of natural resources and guaranteeing future generations the opportunity to fairly enjoy the resources of the world [28]. Under its guidance, the sustainable development level of the YRD has been continuously improved. In 2006, the *China Urban Sustainable Development High-level Forum* released the *Empirical Analysis of the Sustainable Development of Cities in the Yangtze River Delta*, which comprehensively evaluated the sustainable development level of the 16 cities in the YRD and encouraged governments at all levels to consciously adhere to the environmental as well as the economic and social aspects of the practical approach to coordinated development. The incorporation of green quality into the index system of comprehensive and fundamental modernization as well as the holding of joint meetings, among others, have prompted environmental protection cooperation in the YRD to enter a substantive start-up stage [29]. In June 2020, the ecological environment departments of the three provinces and one city jointly signed the *Work Memorandum on Coordinating and Promoting the Integration of Ecological and Environmental Administrative Penalty and Discretionary Benchmarks in the Yangtze River Delta Region*, which emphasized the deepening of cross-regional cooperation in ecological and environmental protection, therefore resolutely winning the battle against pollution in the YRD in order to jointly protect the lifeline of sustainable development and to ensure that natural resources can be enjoyed equally between generations.

However, it is often difficult for a single local government to solve eco-environmental problems across administrative regions, mainly to deal with the issue of diffuse environmental pollution. Intergovernmental cooperation and collaborative governance are much more needed. In 2011, *China's Peaceful Development White Paper* put forward the new perspective of "a community of a shared future" and called for the gradual formation of a global value for jointly addressing human challenges and realizing the common interests of humanity. Thus, under the guidance of the concept of "a Community with a Shared Future for Mankind", the local governments of the YRD strengthen the citizens' awareness of "a community of ecological destiny" in the region and actively create a supervision model that integrates eco-protection red lines [27]. The YRD, in its creation of the legal system, further enshrines the concept of a "community of common ecological destiny" and emphasizes a green lifestyle. The *Yangtze River Delta Eco-Green Integrated Development Demonstration Zone* was launched on 31 October 2020. The first draft of land and space planning was compiled across provinces and were made legally effective, resulting in a unified preparation, joint approval, and joint implementation. Meanwhile, government departments around the YRD continue to improve the environmental education system, environmental protection awareness, knowledge, ethics, and the social responsibility of stakeholders in order to grow the value of sustainable development and explore the construction of a "community of common ecological destiny".

3.2.4. Action Mode: From Authoritarianism to Co-Governance by the Whole People

Today's international environmental governance situation is changing day by day. As a representative of developing countries, China has consciously increased pressure to reduce emissions. It has also strengthened its determination to improve its independent national contribution to global energy conservation and the emission reduction process. At the *Climate Ambition Summit* in December 2020, the Chinese leader committed that carbon dioxide emissions per unit of GDP will fall by more than 65% by 2030. The YRD, as a key region for energy conservation and emission reduction in China, plays a "pioneer" role in the development, transformation, and comprehensive reform process. From Table 6, we can see that "authority-led" accounts for the most significant proportion of policy coding in the action mode, which appears 66 times in the policy text, and emphasizes the role of organizational leadership in the collaborative governance of the YRD environment. The second is that "social participation" appeared 55 times and was gathered in the second half of the year, emphasizing public participation in environmental protection governance. Finally, "international cooperation" has the fewest occurrences and is the new focus of current policy attention. In the YRD, there has been no policy synergy. Therefore, to achieve the expected energy conservation and emission reduction goals, the YRD's environmental collaborative governance policy is constantly innovating, changing from authoritarianism to co-governance.

Table 4. Formulation of local standards and central documents for rural domestic sewage treatment in the YRD.

Area	Local Standards and Central File Names	Promulgating Unit	Current Progress	
			Released	Implemented
Zhejiang	*Discharge Standard of Water Pollutants for Rural Sewage Treatment Facilities DB 33/973—2015*	*Zhejiang Provincial People's Government*	29 June 2015	1 July 2015
Shanghai	*Discharge Standard of Water Pollutants for Rural Sewage Treatment Facilities 31/T 1163—2019*	*Shanghai Administration for Market Regulation*	14 June 2019	1 July 2019
Anhui	*Discharge Standard of Water Pollutants for Rural Domestic Sewage Treatment Facilities DB34/3527—2019*	*Anhui Provincial Department of Ecology and Environment* and *Anhui Provincial Administration for Market Regulation*	25 December 2019	1 January 2020
Jiangsu	*Discharge Standard of Water Pollutants for Rural Domestic Sewage Treatment Facilities DB32/3462—2020*	*Jiangsu Provincial Department of Ecology and Environment* and *Jiangsu Provincial Administration for Market Regulation*	13 May 2020	13 November 2020
Central Committee of the CPC	*Guiding Opinions on Promoting Rural Domestic Sewage Treatment*	Nine departments, including *the Central Agricultural Office*	July 2019	
Central Committee of the CPC	*Notice on Accelerating the Formulation of Local Rural Domestic Sewage Treatment and Discharge Standards*	*Ministry of Ecology and Environment* and *Ministry of Housing and Urban-Rural Development*	August 2020	

Table 5. "Issue orientation" node hierarchy and coding information table.

Node	Child Node	Reference Points	Coding Example
Issue orientation	Energy conservation	68	About encouraging the development of emerging environmentally friendly industries
	Technological innovation	39	Strengthening scientific and technological support for the prevention and control of hazardous waste pollution
	Ecological innovation	36	Further promotion of the pilot project of horizontal ecological compensation in the upper and lower reaches of the Xin'an River
	Sewage permit	29	Accelerating the implementation of the pollutant discharge permit system
	Protection priority	28	Adhering to the priority of protection and implementing the red line of ecological protection
	Environmental credit	22	Strengthening the responsibility of polluters; improving the environmental protection credit evaluation, mandatory information disclosure, severe penalties, and other systems
	Community with a shared future for mankind	5	The construction of ecological civilization is an important part of building a community with a shared future for mankind

Table 6. "Action Mode" node hierarchy and coding information table.

Node	Child Node	Reference Points	Coding Example
Action mode	Global Cooperation	10	Strengthen international environmental cooperation; deepen international cooperation and exchanges on disaster prevention and mitigation
	Authority Dominates	66	Strengthen organizational leadership; give full play to the role of the central and local regional coordination mechanisms
	Social Engagement	55	Strengthen public participation; promote general understanding and participation in environmental protection governance

In the environmental governance model under authoritarianism, the government assumes the leading role in policy formulation and implementation. Other subjects are on the verge of losing their sense of participation. The government takes advantage of "concentrating efforts to do big things" and can achieve emission reduction targets in a short period under certain circumstances. For example, in order to ensure the smooth holding of the *2014 Nanjing Youth Olympic Games*, the environmental protection departments of the three provinces and one city jointly discussed the *Nanjing Youth Olympic Games Environmental Quality Collaboration Guarantee Plan*, shared air quality data and pollution source emission lists, and protected the high-quality eco-environment during the games. However, it is challenging for authoritarianism to guarantee the long-term effectiveness of green co-insurance, and environmental governance in the YRD has long faced the problem of a rigid stripe structure. The fragmentation of environmental governance authority results from the increasing competition and conflict among stakeholders in the decision-making process [30]. The report from the *19th National Congress of the CPC* in 2017 recommended "adhering to joint governance by all people and prevention and control at the source". The local governments of the Yangtze River Delta actively responded to the call, advocated for the pursuit of the value of co-governance by the whole people, and guided and encouraged enterprises, the public, new media, NGOs, and other entities to engage in specific actions in the formulation and implementation of environmental governance policies. In August 2020, Zhejiang Province issued the *Implementation of Opinions on Establishing and Improving the Discovery Mechanism for Environmental Pollution Problems*, requiring the government, market, and society to collaborate and participate in constructing the environmental governance mechanism. The leading role of "responsibility" emphasizes the precise assistance and implementation of the main responsibility of enterprises, enhances the ability of the masses to participate, introduces private funds to allocate ecological monitoring equipment, etc., in order to ensure the effective operation of the public supervision mechanism for environmental governance. To ensure the efficient operation of the public supervision system for environmental governance, the government strengthens the leadership role by emphasizing precise assistance and action on the enterprises' part, by improving the ability of the masses to participate, and by introducing private funds to allocate ecological monitoring equipment.

3.2.5. Policy Instruments: From Institutional Norms to Propaganda and Guidance

In China, the implementation of environmental pollution control adopts a dual-track responsibility mechanism. The party and the government share the same responsibility. The newly revised *Environmental Protection Law* in 2015 clarifies the government's responsibility for the supervision and management of environmental protection. According to the *Accountability Regulations of the CPC* in 2016, those who provide poor leadership or make serious mistakes in promoting the construction of eco-civilization should be held responsible for severe losses. According to the *Measures for the Evaluation and Assessment of Ecological Civilization Construction Objectives* in December 2016, the party and the government are responsible for evaluating and assessing eco-civilization [31]. Using a dual-track responsibility mechanism, public officials can effectively supervise the implementation of their policies. In addition, it can effectively reduce the speed of "oasis degradation" and ensure the integrity of ecological balance.

Environmental inspectors and official assessments guaranteed the mechanism. On the one hand, "Environmental Protection Inspector" started as a pilot project in Hebei Province in 2015 and officially entered all provinces across the country. Among them, the environmental protection inspection work in the YRD was highly valued by the *Central Committee of the CPC*. Can ecological stability be maintained under the premise of rapid economic development? The public information facilitated by environmental inspectors stationed in the YRD is an example of coding (Table 7). The analysis of the coding results shows that the reference points for "coordinated supervision" and "legal system construction" are the largest, appearing 157 times in the policy text. The data shows that our country attaches high importance to constructing and improving institutional norms of "laws to follow and strict enforcement". Although "propaganda and guidance" does not appear often, it has been frequently mentioned in recent years, and the trend toward concentration is evident. Therefore, to implement the requirements of the integrated development of the environment, the YRD has gradually changed the focus of policy measures, moving from institutional norms to publicity and guidance.

Table 7. "Policy instruments", node hierarchy and coding information table.

Node	Child Node	Reference Points	Coding Example
Policy instruments	Legal construction	76	Deepen the reform of the ecological civilization system and improve the long-term governance mechanism (Zhejiang August 2017)
	Official assessment	63	Strengthen responsibility and assessment (Anhui April 2017)
	Environmental inspector	20	Improve political standing and resolutely shoulder the political responsibility of inspectors and rectification (Jiangsu May 2018)
	Collaborative supervision	81	Strengthen law enforcement with an iron fist and continue to increase environmental supervision (Shanghai November 2016)
	Publicity and guidance	33	Increase efforts to solve outstanding ecological and environmental problems around the masses and strive to improve the comprehensive management of the ecological environment (Anhui October 2018)

On the other hand, the number of reference points for "official assessment" ranks third among the total nodes of policy measures. The achievement of local eco-civilization is linked to the efforts of officials, as it was mentioned 63 times. Such an approach is conducive to the further improvement of the efficiency of local governments in dealing with environmental pollution problems. By way of example, in 2014, the *Measures for Assessing the Implementation of the Air Pollution Prevention and Control Action Plan* was implemented, which effectively stimulated the interest of environmental law enforcement officers. By 2016, the scope of assessment was expanded, and a formal and unified target evaluation system was formulated, namely the *Method for Evaluation and Assessment of Ecological Civilization Construction Objectives*, to further strengthen the assessment of joint prevention and control and to enhance the endogenous driving force for the collaborative environmental governance of local governments [32]. Since 2018, the YRD has been designated as the subject of collaborative assessment. $PM_{2.5}$ in the YRD was released by the *Ministry of Ecology and Environment*, emphasizing the policy direction of joint air pollution prevention and control in the YRD. In addition, governments established the dual-level performance structure of "ecology and economy" [33], substantially promoting the unification of economic, social, and ecological benefits.

Although the government's role in collaborative environmental governance has gradually emerged and improved, the public nature of environmental governance indicates that government failure is inevitable. This requires stakeholders to participate, supervise, and govern together. The current policy texts, however, emphasize administrative and market means to curb other entities' pollution discharge behavior. The specific procedures, methods, and degrees of public participation in environmental governance are not well-regulated, and the results are minimal. As one of the objects of environmental policy implementation, the public is both the participant and victim of pollution behavior. There is an urgent need for the effective implementation of environmental policy. Therefore, the public should be the most active policy responder. At the policy design level, more attention should be paid to ensuring the correct publicity and guidance for the public and to the gradual increase in the intensity of advertising and education. In August 2020, Anhui Province issued the *Notice on Printing and Distributing the Overall Emergency Response Plan for Anhui Province Emergencies*, which pointed out that emergency command agencies at all levels should formulate a unified information release and public opinion guidance plan. The main ways for the public to participate in the construction of ecological civilization include legislative participation, decision-making participation, and execution participation [34]. To achieve this objective, the government must provide transparent affairs, guide public opinion, promptly promote other regions' work results, and actively create an environment where the whole society could jointly supervise and participate in environmental governance.

4. Discussion

4.1. Environmental Collaborative Governance Policy and Environmental Performance

Environmental performance is the measurable effectiveness of an environmental management system based on environmental objectives and factors. It is used to express the actual environmental consequences related to the level of effort and quality of work. It should be said that environmental performance is the ultimate criterion for evaluating environmental policies [35]. Environmental policy yields huge benefits. Environmental sustainability is closely related to environmental policies, for example, policies that prevent food waste significantly reduce environmental consequences [36], policies that effectively manage natural resources can transform the resource curse into national well-being [37], and policies that build ecology effectively improve the ecological footprint [38].

After more than three decades of promoting collaborative environmental management, the environmental conditions in the YRD have improved significantly, with an effective initial treatment of air, water, and soil pollution. One study found that regional integration gradually contributed to the improved environmental performance [39]. The YRD has also seen steady growth in environmental performance in the recent years [40]. Because this study focuses on the analysis of environmental collaborative governance policy texts, environmental performance was not examined. However, environmental performance, as a reflection of the effectiveness of environmental policy implementation, may be of guidance for future environmental policies. Therefore, the next research should focus on studies that measure how much of an impact these environmental collaborative governance policies have actually had on the environment.

4.2. The Future Direction of Environmental Collaborative Governance Policy

In analyzing the internal logic of relevant policy texts on collaborative environmental governance, it was found that the ability of collaborative environmental governance in the YRD has gradually strengthened as it responded to the strategic direction of the integration of the YRD and the joint regional development. It has become a practical approach to cross-domain environmental governance issues. However, restrictive factors and governance bottlenecks still exist in implementing specific policies. Due to the different stages of economic development, regulatory systems, institutional environments, and governance demands in the YRD, the preferences, models, and behaviors in ecological environment governance are quite different. Summarizing the results of policy text analysis, collaborative environmental governance in the YRD should be comprehensively deepened in the three dimensions of decision-making, implementation, and supervision in order to promote the simultaneous improvement of the speed and efficiency of collaborative environmental governance (Figure 6).

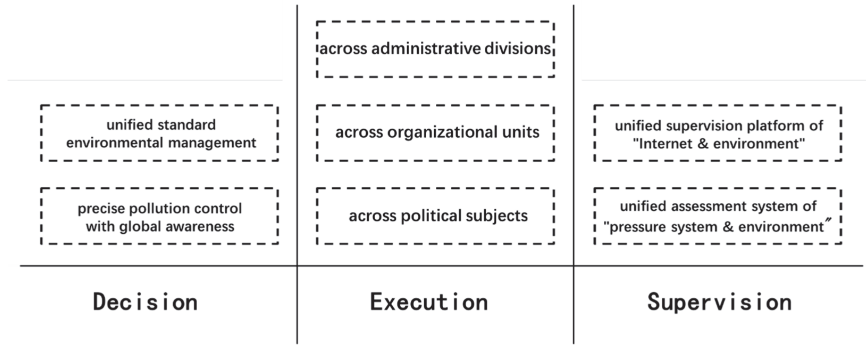

Figure 6. The path for improving collaborative environmental governance in the Yangtze River Delta.

4.2.1. Decision: Unified Standard Environmental Management and Precise Pollution Control with Overall Awareness

Environmental standards are an invaluable bridge for constructing the environmental legal system [41]. They provide an objective basis for environmental law enforcement and help to promote the effectiveness of regional environmental collaborative governance [42]. The YRD has formulated different local standards for environmental issues. As an example, with regard to the emission of particulate matter in the *Pollutant Emission Standard for Biopharmaceutical Industry,* the standard value in Shanghai far exceeds that in Zhejiang and Jiangsu [43]. Different environmental standards can easily lead to the transfer of pollution. In the process of eliminating outdated production capacity in areas with high environmental standards, high-polluting enterprises are transferred to surrounding areas with lower environmental standards. Overall, the pollution situation in the YRD has improved, but the pollution sources have not been effectively controlled. In response to the conflict of environmental standards in the YRD, the *State Council* issued the *Outline of the Yangtze River Delta Regional Integrated Development Plan*, proposing to build a "high-level ecological and green integrated development demonstration area in the YRD" and to formulate a unified environmental access in the integration standard. Facts have proved that only by carrying out strict and unified centralized environmental management and by actively promoting the formulation of a negative list for industrial access in critical ecological function zones can we effectively alleviate the transfer of pollution sources and narrow the wide gap in environmental quality among the three provinces and one city [44].

The *19th National Congress of the CPC* and the *Fourth Plenary Session of the 19th Central Committee* took an initial step toward modernizing the eco-environment governance system and enhancing its capacity, acknowledged the close connection between precise pollution control and eco-civilization, and scientifically understood pollution in the three major fields of air, water, and soil. Thus, the essentials of governance coordination were established. Through the analysis of policy texts, it was found that the pollution problems commonly faced by the YRD include domestic garbage, waste pollution, nuclear radiation, heavy metals, etc., in addition to the three basic areas. The YRD addresses the environmental problems in a more overall and long-term fashion as part of their overall environmental governance process.

4.2.2. Execution: Three-Dimensional Coordination and Linkage of Environmental Coordination Mechanism

It is difficult to manage the environment of the YRD because the regulatory systems are independent of each other, and the implementation methods are entirely different. The solution to the policy design lies in the construction of a three-dimensional coordination and linkage mechanism for environmental governance across administrative divisions, organizational departments, and political entities. A multi-subject approach to policy formulation and implementation helps to overcome the problem of "adjacent but uncoordinated" metropolitan circles [45]. Since pollution is transboundary, public, and uncertain, the local government must extend beyond urban to multiple regions and at various levels [5] to expand public participation in policy formulation and implementation. (1) Geographically, the environmental governance of the YRD spans the administrative divisions of many provinces and cities, no longer adopts administrative units as the governance object, and pays more attention to the cooperation between critical provinces and cities. For example, through city environmental planning in relation to Shanghai, Nantong has broken the inherent shackles of narrow environmental governance and the effects of weak governance. (2) In terms of functions, governments strengthen the mechanism for cooperation and negotiation across organizational officials and break the inter-office barriers in environmental governance. As a result of realistic dilemmas such as relationship prevarication, tension, contradiction, and sluggishness, law enforcement methods, approaches, and strengths are put together and form a full-fledged cooperation mechanism between various departments. (3) In terms of roles, based on the concept of a community with a shared future for mankind, the eco-environment was formed to be inclusive. The environmental governance situation requires, for the collaborative governance of the YRD's environment, the imperative construction of a comprehensive framework that involves multi-subject participation [46], the maintenance of the government's authority and dominance as a decision-maker, and the fostering of awareness and involvement in social organizations and the public through publicity, education, and technological innovation.

4.2.3. Supervision: The Unified Supervision Platform of "Internet + Environment" and the Unified Assessment System of "Pressure System + Environment"

The *14th Five-Year Plan* emphasizes the critical position of ecological green development in the national development strategy, which has made ecological supervision a critical link in environmental governance. Based on the existing meteorological business platform in the YRD, it will support the sharing of the YRD's environmental data. This will improve the ability to observe pollution transportation networks. At present, China's environmental governance is undergoing an informatization process. Accelerating the establishment of an environmental credit resource database and realizing a unified "Internet + environment" intelligent supervision platform is conducive to the realization of public participation and collaborative supervision. A unified performance appraisal mechanism of rights, responsibilities, and interests should be established within the scope of the YRD with the help of a data-sharing platform. Positive list systems should be encouraged in the assessment of project environmental impact in order to boost the YRD's environmental impact. The incentive and competitiveness of the supervision mechanism [47] includes the evaluation of enterprises and public representatives in the official evaluation system, gives local government officials a higher evaluation weight for environmental governance efficiency, optimizes the procedures and structure of high-quality development performance evaluation, and integrates environmental governance.

5. Conclusions

Environmental policies in the Yangtze River Delta have undergone significant changes over the past three decades. This study analyzed the logic of policy changes in five dimensions. The trajectory of policy change transitioned from decentralization to authority; the function positioning changed from universality to precision; the issue orientation expanded from sustainable development to a community of common ecological destiny; the action mode advanced from authoritarianism to co-governance by the whole people; the policy instruments changed from institutional norms to propaganda and guidance.

The purpose of policy text analysis is to put forward policy suggestions. Government efforts in the future will be directed to improve on the unified standard environmental centralized management, to improve decision-making mechanisms for precise pollution control with global awareness, and to integrate regional, functional, and role-based environmental coordination and implementation mechanisms; they will also be establishing the unified assessment and oversight mechanisms of "pressure system + environment" and integrating the unified supervision platform of "Internet + environment".

Future research on environmental collaborative governance policies in the YRD could be directed toward the study of the environmental performance generated by the policies. How to scientifically quantify the environmental performance resulting from these policies is still a scientific question that can be discussed.

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Article

An Evaluation and Optimization of the Spatial Pattern of County Rural Settlements: A Case Study of Changshu City in the Yangtze River Delta, China

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Abstract: The development model of rural settlements in economically developed regions has reference and guiding significance for other developing rural settlements. The study was conducted to discuss the spatial distribution and scale structure evolution characteristics, in order to understand the development process and the problems of rural settlements in Changshu City, Jiangsu Province. Then, based on the multi-stage goals of Rural Revitalization of "pole–field–zone–network", a multi-stage rural settlement spatial structure was revealed to promote the optimization of settlement layout and promote urban–rural integration. The data of rural settlements were extracted from the land use data of nearly 20 years from 2000 to 2020. Different research methods were utilized for the study. The results revealed that the spatial pattern and scale structure of rural settlements in Changshu had experienced two periods of drastic changes and stable adjustment in the past 20 years. The rural settlement density generally presented a spatial pattern of dense in the north, sparse in the South and sparse in the East. The scale system of rural settlements tended to disperse from centralization, but the spatial agglomeration was enhanced. Finally, based on the above research results and problems, a "pole–field–zone–network" multi-stage settlement structure was revealed, which helps to form a reasonable urban and rural network.

Keywords: rural settlements; evolutionary pattern; spatial structure; Changshu City

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1. Introduction

The countryside is a spatial territorial system, referring to the territory where agricultural production is the main focus. Rural settlements are the main object of rural geography. As places where working people, mainly in agricultural production, live together [1], they are the basic units in the construction of rural revitalization. In recent years, the rapid development of urbanization has a more and more significant impact on the spatial form and function of rural settlements in county areas. With the seasonal migration of the population, a certain decline phenomenon, the phenomena of "hollow village" and "rural disease" appear in the rural settlement space, which seriously restrict the sustainable development of rural economy and society. Therefore, the optimal layout of rural settlements is conducive to the effective use of rural land and resources. The Chinese government has optimized the rural settlement space through a series of top-level design strategies such as human settlement environment improvement, rural revitalization and urban–rural integration [2,3]. The pattern evolution of rural settlements in terms of location, scale, distribution, structure, form and function can reveal the footprint of human–land interaction in different stages and regions [4]. The layout optimization of rural settlements largely depends on the understanding of the spatial evolution of rural settlements and the accurate prediction of their future development trend [5]. If there is insufficient understanding of the spatial evolution and optimization rules of rural settlements, it is difficult to solve the problems of rural development, and it will also lead to problems of man–land relationship in practice. With the tremendous changes in the man–land relationship in China, rural settlements, as the spatial carrier of social and economic development, are facing drastic differentiation and reorganization [6]. The spatial evolution and optimization rules of rural settlements at county level are actively explored, so as to provide a scientific basis for the practice of urban and rural development in China.

The study of the spatial evolution pattern and optimization of rural settlements has always been a hot topic in academic circles. As early as the 19th century, foreign scholars began to study rural settlements. The study turned from the description of the relationship between rural settlements and the natural environment to the analysis of the spatial distribution, evolution, social and economic reconstruction of rural settlements and the interaction of factors [7,8]. From the end of the 19th century to the 1940s, settlement geography gradually developed into an independent science of human geography. The main research contents of rural settlements included the morphological characteristics of settlements and their relationship with the natural environment. The research on the materialization of rural settlements first focused on the study of rural settlements and landscapes [9–11]. In the 1950s and 1960s, the quantitative and scientific analysis of geography was strengthened, and the methods for measuring the scale, form and distribution of rural settlements became increasingly complex [12–16]. Since 1970, the concept of sustainable development and the emergence of environmental pressure have boosted the research on rural sustainable development, and the development of rural geography has seen the phenomenon of "regeneration" [17,18]. Since the 1990s, foreign scholars have gradually integrated multiple disciplines into the study of rural settlements. Rural Realism, written by CIoke [19] et al., focused on the integration of rural geography and cultural geography. Seymour [20] also emphasized the loosening of the boundary between cultural geography and rural geography in the seminar on the theoretical development of cultural geography, and some commentators also recognized the cultural turn of rural geography [19,21,22]. The research content involves rural settlement policy [23], rural development [24] and other aspects. In the early to mid 1990s, a large number of scholars had realized that rural studies have or will have the characteristics of postmodernism [19,25,26]. Subsequently, many scholars began to study rural reconstruction and rural diversity [27–37]. The research content also involved the evolution of rural settlement patterns [38], rural conflicts [39], local governments and rural discourse rights [40], etc. Since the 21st century, relevant scholars have analyzed the development and evolution of rural geography in the United Kingdom [41] and the United States [42,43] from different perspectives. Studies on rural settlement space showed an unbalanced development trend [44–46]. Rural environment had a substantial impact on people whose work and life were dominated by rural space, while the elimination of regional characteristics ignored the physical characteristics of rural environment [47]. In the past decade, under the background of global climate change and food crisis, rural sustainable development [48–50], rural land use optimization [51], rural infrastructure construction [52] and other contents have attracted great attention. The research content of rural settlements is richer, the research perspective is more micro, and the research methods are more diversified.

Studies on the spatial evolution and optimization of rural settlements in China began in the 1930s. At that time, the theory of man–land correlation of the French school was introduced into China, and *The Principles of Man–Earth* was translated into Chinese by Bernard. The book expounded rural settlements and the relationship between and human activities and the environment in a large number of pages, which had a wide impact on the Chinese geography field. After reform and opening up, the economic and social transformation has led to great changes in the rural areas of China, and the research on settlement formation, settlement system, settlement form and type has been greatly developed [53,54]. The urbanization boom since 1990 has made an impact of urbanization on rural settlements, and the research contents have been extended to rural urbanization, spatial structure of settlements, expansion of settlement land, urban–rural integration, settlement evolution and its dynamic mechanism [55,56]. Since the 21st century, under the guidance of new concepts such as urban–rural integration, construction of a new socialist countryside and construction of a beautiful countryside, the research on rural settlements has developed rapidly and the research content has become richer. In the past decade, domestic research had gradually paid attention to the comprehensive and integrated analysis of RS, GIS, fractal theory, rank–scale law, landscape index and other methods, focusing on arid oasis areas [57], ecologically fragile areas [58–60], mountainous areas [61,62], watershed and lake areas [63], and traditional agricultural areas [64,65], economically developed areas in eastern China [66], and areas with ethnic minority characteristics [67], etc. The research explored the spatial evolution of rural settlements, rural settlement ecology, rural communities, rural settlement landscape, rural settlement hollowing out, rural settlement planning organization, driving mechanism, and spatial optimization [68–76]. Through the study of these contents, the spatial problems of rural settlements can be recognized, and the spatial rules of settlements can be found, which can be applied to the practice of urban and rural development and management.

Under the influence of urbanization and industrialization, the spatial evolution characteristics of the rural settlements in economically developed areas are different from structure characteristics in traditional agriculture areas. Considering interaction between towns and villages, the paper uses the field strength model to measure the radiation range, identifies the rural growth pole, defines villages space field, divides rural development area, and forms a complete set of the urban and rural infrastructure network. Through the content of study, the spatial evolution of rural settlements can be recognized. Moreover, the direction of rural settlement layout optimization can be determined. The research can be applied to the practice of urban and rural development and management.

The spatial evolution of rural settlements in counties reflects the comprehensive relationship between human activities and natural and social environments. The optimization of rural settlement space is not only conducive to improving the intensification of local land use, but also can create necessary conditions for the development of rural industries, the improvement of human settlement environment, the improvement of public service facilities and other social and economic reconstruction [6]. The Yangtze River Delta region is one of the most economically developed regions in China. The county economy has developed well, and the rural development has also undergone a process of transformation and development. As an important county-level city in the Yangtze River Delta, Changshu has a developed economy, dense rural settlements, high land development intensity. It is greatly influenced by natural and human social environment, forming a diversified spatial pattern of rural settlements. The main objective of this paper is to explore the spatial evolution characteristics of rural settlements in Changshu City based on the land use data of rural settlements in nearly 20 years from 2000 to 2020. Considering the acquisition of data and avoiding the incompleteness of short-term scale, 2000, 2010 and 2020 are selected as research nodes to explore the spatial evolution characteristics of rural settlements in Changshu City. The spatial optimization measures of rural settlements based on the "pole–field–zone–network" are revealed. The overall objective of this study is to provide scientific reference for the development planning of rural settlements in Changshu City.

2. Optimization Logic

The theory of point–axis progressive diffusion emphasizes that central cities at all levels are connected through development axes such as transportation lines to form a point–axis system. With the deepening of development, the contradiction of benefit distribution or the intermediary opportunities, the relatively small-scale new gathering points will continue to form, the development axis will be further extended, and finally, the whole region will form a point–axis spatial structure of different levels [77]. The interweaving of multiple point–axes eventually forms a network, and thereby further develops to form the spatial structure of a regional network. The essence of urban–rural integrated development lies in giving full play to the diffusion effect on the basis of strengthening the polarization of the urban–rural regional system, and forming the three-dimensional space and network effect of urban–rural development [78]. The rural regional system is a multi-body system composed of urban–rural integration, rural complex, village and town organisms, and residential and industrial synergies. Based on the multi-body system, the multilevel objective system of "pole–field–zone–network" constructed from the edge to the center by the urban and rural basic network, rural development zone, village space field and rural revitalization pole can effectively guide the formation of a reasonable spatial structure of towns and villages [79].

The county is the relatively complete and most stable regional unit in China's administrative division. It encompasses a comprehensive system of urban and rural settlements in scale and is a key link in coordinating urban and rural development, as well as an important unit in promoting rural revitalization [80]. Since 1978, with county towns as the center and towns with different functions as the core points, China has gradually formed a space for coordinated development between urban and rural areas with a clear structure, close connections and convenient transportation based on the rational layout and effective organization of land use [81,82]. In this study, the multi-stage system of "pole–field–zone–network" is applied to the urban–rural spatial structure at the county scale. Specifically, the central city plays a leading and coordinating role. The "pole" is the town under the county, connecting the city and the countryside, and is the nucleus leading the development of the countryside. The "field" refers to the town's spatial radiation to the countryside. The "zone" refers to the rural development area under the town's influence. The "network" refers to the transportation network and public service facilities that facilitate the flow of city–town–village factors. One reveals the multi-stage spatial structure of urban and rural areas in order to promote the optimization of rural settlement layout.

3. Materials and Methods

3.1. Study Area

Changshu is a county-level city under the jurisdiction of Suzhou City, Jiangsu Province, 100 km from Shanghai, with a land area of 1276.32 km^2. As one of the top 100 counties in China, the area has a high level of agricultural modernization and is a pilot county in Jiangsu Province for the construction of agricultural modernization. By the end of 2020, the GDP of the region was 236.543 billion yuan, and the proportion of the three industries in GDP was 1.71:48.45:49.84. There were 1.0641 million registered residents and 1.6772 million permanent residents. The urbanization rate was 73.37 percent, 0.27 percentage points higher than it was at the end of last year. It should be noted that the administrative division of Changshu City has changed, with twenty-four towns under its jurisdiction in 2000 and ten towns in 2005. By the end of 2020, Changshu had jurisdiction over eight towns and six streets. In this paper, based on the stability of administrative divisions and to ensure uniformity of research, the administrative divisions of Changshu in 2005 were used as the basis (Figure 1), and relevant data were categorized according to their corresponding administrative divisions.

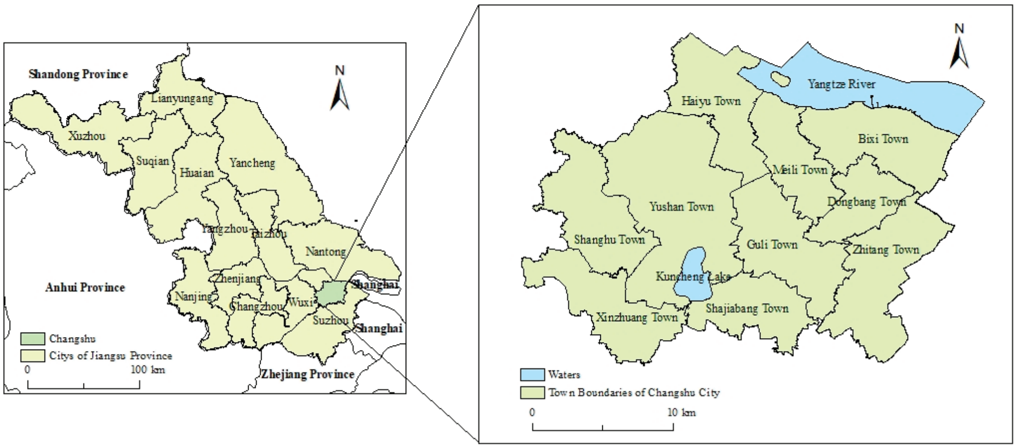

Figure 1. Location of areas covered in Changshu City. Note: "Waters" are open water bodies for ecological protection and ports.

3.2. Data Source

The study data included socio-economic data, rural settlement land use data, and the basic geographic information data of Changshu City. Socio-economic data were from the Jiangsu Statistical Yearbook 2021, the Suzhou Statistical Yearbook 2021, and Changshu National Economic and Social Development Statistical Bulletin 2020. The land use data of rural settlements were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 3 June 2022). The land use data of Changshu City in 2000, 2005, 2010, 2015, and 2020 are extracted. According to the basic characteristics of the number and scale changes of rural settlements, the rural settlements in 2000, 2010, and 2020 were selected as the research object. The spatial resolution of the data was 30 m. It was constructed based on Landsat Image data and human–computer interactive visual interpretation. The basic geographic information data included the administrative boundary data of Changshu City and the administrative boundary data of the town areas under its jurisdiction.

3.3. Methods

3.3.1. Nuclear Density Estimation

Kernel Density Analysis is mainly applied to the continuity representation of spatially discrete data. Rural settlements have the basic characteristics of being spatially discrete and extensive, and their spatial and temporal unity and continuity are difficult to identify visually [70]. The Kernel Density Estimation Method can effectively and intuitively reflect the spatial variability and continuity of the density distribution of rural settlements. The calculation formula is as follows:

$$f(x,y) = \frac{1}{nh^2} \sum_{i=1}^{n} k\left(\frac{d_i}{h}\right) \tag{1}$$

In Formula (1): $f(x,y)$ is the density estimate located at (x,y) position; n is the observed value; h is the bandwidth or smoothing parameter; k is the kernel function, and d_i is the distance of (x,y) position from the ith observed position (unit: pcs/km^2). After many experiments, the search radius was set as 2 km, and the natural fracture point method was used to classify the nuclear density into four grades.

3.3.2. Fractal Dimension

Rural settlements, like urban settlements, are equally hierarchical and show specific patterns in space [83]. In 1949, Zipf proposed the generalized law of scale distribution, $P(r) = P_1/r^q$, and by taking the logarithm of both sides, the relation is transformed into:

$$\ln P_r = \ln P_1 - q \ln r \quad (2)$$

In Formula (2): r = 1,2,3, ... n; $P_{(r)}$ is the size of the rank r colony; P_1 is the first colony size; and q is the Ziff index, which measures the degree of equilibrium in the distribution of colony sizes. The Ziff formula also obeys the power law and has fractal significance. Hausdorff's fractal dimension D and q are reciprocal [84].

According to the study [85], the size of the D-value has a clear geographical significance and can characterize the hierarchical scale structure of the settlement system. If the value of D is less than 1 (q is greater than 1), it means that the distribution of the hierarchical scale of the settlement system in the region is relatively scattered, with a large degree of variation in the scale of the sites and a strong monopoly of the first settlement. Conversely, it means that the distribution of the scale of the settlements in the region is relatively concentrated, with a balanced distribution of sites and a large number of settlements in the middle order.

3.3.3. Space "Hotspot" Detection

Global spatial autocorrelation was used to measure the global pattern of rural settlement size in a region. Local Getis-Ord G* can further detect the spatial dependence of rural settlement size in a local area and use spatial visualization to reveal whether there are local "hot spots" or "cold spots" of high- or low-value clustering. The mathematical model is as follows [86]:

$$G_i^*(d) = \sum_{i=1}^{n} w_{ij}(d)x_j / \sum_{j=1}^{n} x_j \quad (3)$$

In Formula (3): $G_i^*(d)$ is the local test value, x_j is the area of the rural settlement, $w_{ij}(d)$ is the distance weight, and n is the number of rural settlement patches. To facilitate interpretation and comparison, $G_i^*(d)$ is normalized to obtain $Z(G_i^*)$, a hot spot area if the Z value is positive and significant, and a cold spot area if the Z value is negative and significant.

3.3.4. Field Strength Model

In the township village system, the development of the township center has a certain capacity for agglomeration and radiation. Its sphere of influence is an important basis for the division of the village spatial field and the rural development area. The field strength model focuses on the influence and radiation of the township on the surrounding area, and follows the "law of distance decay." Borrowing from physics, the hinterland of a township is referred to as the "force field" of the township's influence, and the magnitude of that influence is referred to as the "field strength" [87]. The calculation formula is as follows:

$$F_{ik} = Z_i / D_{ik}^{\beta} \quad (4)$$

In Formula (4): F_{ik} is the field strength of township i at point k; Z_i is the combined scale value of township i, with the introduction of the township potential index as a proxy; D_{ik} is the distance from township i to point k; and β is the distance friction coefficient, which generally takes the value of 2 [88].

Considering that traditional field strength models used distance algorithms that tend to ignore spatially extended dissimilarities, this paper used minimum time distances instead of straight-line distances to mitigate this limitation. Due to the differences in the time cost of travel on different land use types, drawing on the research methods of Zeng [89] and Yin [90], based on the accessibility of data, the speed of road access was set to 60 km/h for roads and 40 km/h for rural roads, and the barrier factors such as land and water outside road traffic had less impact on accessibility, and the area outside road traffic was treated as 6 km/h on foot. A grid size of 10 m × 10 m was selected, and the speed of the cost factor to the time spent travelling the grid cell was converted using the formula cost = 1⁄(V × 60). The spatial expression of the accessibility cost was achieved through the raster cost weighted distance function in ArcGIS 10.5, which found the minimum time distance parameter D required in the field strength model.

4. Results and Analysis

4.1. The Evaluation of Spatial Pattern and Scale Structure of Rural Settlements

4.1.1. Evolution Characteristics of Spatial Pattern of Rural Settlement Density

In terms of spatial pattern, the distribution of rural settlement density in Changshu in 2000, 2010 and 2020 is similar, showing a spatial pattern of dense north and sparse south, dense west and sparse east, with obvious geographical differentiation, high correlation with water systems and roads, and relative clustering of settlements at the intersection of township administrative boundaries (Figure 2). Specifically, the high and sub high density areas of rural settlements distributed in continuous sheets were mainly located in Meili Town, Haiyu town and Shanghu Town, with a density of more than 1.34 units/km^2 in 2020. In Bixi Town, the junction of Meili Town and Dongbang Town, the northwest of Haiyu Town, the north and southwest of Yushan Town, and the north of Xinzhuang Town, several scattered higher density nuclei were formed, with little continuity. The vast majority of rural settlements in Yushan Town, Guli Town, Shajiabang Town, Zhitang Town, Bixi Town and Dongbang Town were sparsely distributed, with a distribution density of fewer than 0.78 units/km^2 in 2020.

In terms of temporal evolution, the distribution location and size of rural settlement density nuclei have changed significantly from 2000 to 2020. The area of high−density nuclei has gradually narrowed, and the area of low-density nuclei has gradually expanded. However, the value of the density nuclei was increasing, with the highest value increasing from 2.47 units/km^2 to 4.21 units/km^2. The results showed that the number of settlements per unit area in the high−density core area was increasing and the distribution of rural settlements tended to be concentrated. Specifically, in 2000, Changshu had a large number of rural settlements and a wide range of dense settlement areas, with areas with a nucleus density greater than 0.6 units/km^2 widely spread throughout Changshu, with two high−density areas in the north and west. In 2010, the high value of nuclear density increased to 4 units/km^2, but the scope of the high−density area of rural settlements in the north was reduced, from a strip across the towns of Haiyu, Meili and Bixi to a cluster in the town of Meili, and the nuclei in the central and eastern part of Bixi disappeared. Because in 2010, Changshu abolished the town of Bixi and established Bixi Street, which was upgraded to a national economic and technological development zone, the development pattern of township enterprises shifted from scattered to concentrated, capital and population were concentrated, and the built−up area of the town expanded, and the layout of rural settlements changed considerably and transformed into low−density areas. However, at the northwestern end of Haiyu Town, a high-density nucleus appears as the number of settlements increases. In the west, a large part of the high−density nucleus disappears and transforms into a second-highest-density nucleus and begins to be relatively separate. In the central and south−eastern towns, the high-density nucleus almost completely disappears, and especially in Yushan Town and the western part of Guli Town, the low-density range expands significantly, not only because of the expansion of the built−up area of the town, but also, the area is a large lake system and hill area, and the number of rural settlements was decreasing. In 2020, the density distribution pattern of rural settlements was basically the same as in 2010, but the high−density range was further reduced, and the nuclei were more separated. In addition, the high-density nuclei in the northwest of Haiyu Town were increasing.

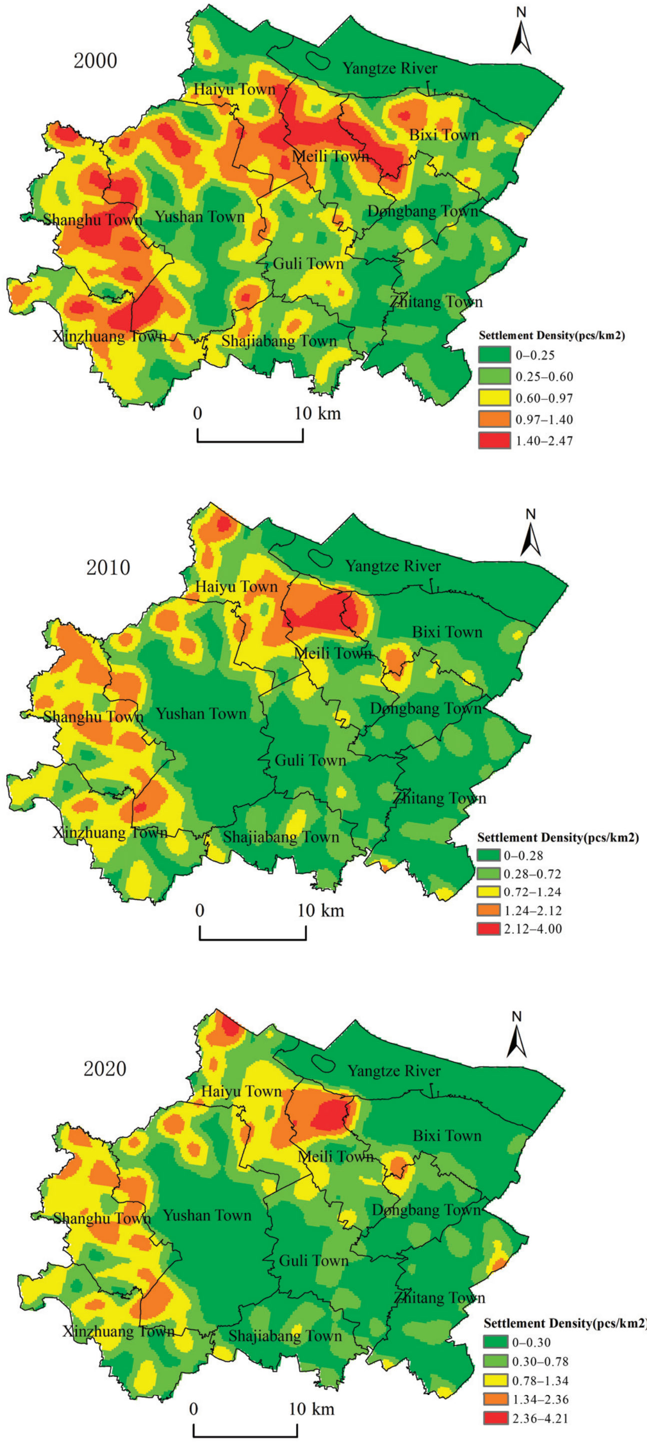

Figure 2. Density map of rural settlements in Changshu.

4.1.2. Evolution Characteristics of Hierarchical Structure of Rural Settlement Scale

The R^2 of the fitted curves was greater than 0.5 and 0.6, which basically conformed to the fractal characteristics [83]. In terms of structural evolution, the fractal dimension of Changshu's rural settlement scale system shows a decreasing trend from 2000 to 2020 (Figure 3), indicating that the polarization of Changshu's rural settlement scale structure has been increasing in the last 20 years, with a large number of new settlement sites being distributed in a concentrated manner. Clustering characteristics toward the first or high-order ranking settlement were apparent [61]. Specifically, the fractal dimension D−value is 1.263 in 2000, 0.901 in 2010, and 0.830 in 2020, which indicated that Changshu rural settlements were relatively concentrated in size in 2000, with a relatively balanced distribution of sites and well-developed small and medium-sized settlements. After 2010, the first and last rural settlements in Changshu tended to be scattered in size, with a wide variation in the distribution of settlement sizes, with large−scale rural settlements prominent, the first settlements holding a monopoly, and small and medium−sized settlements not prominent in development. In 2020, the fractal dimension further decreased, indicating that the scale gap of the first and last settlement in Changshu was still expanding, and the monopoly effect of the first settlement was still strengthening. In terms of structural characteristics, the fractal fitted curves of rural settlements in Changshu in 2000, 2010 and 2020 all showed the "Warping," "Crouching nec" and "Wagging tail" phenomena. "Warping" means that the high−order settlements have primacy and occupy the monopoly position. However, they were still located below the fitting curve, and the actual value is much lower than the theoretical value. "Crouching neck" means that the development of intermediate sequence settlements is not prominent. The "Wagging tail" means that there are more low−order settlements with a more concentrated distribution. However, the size distribution of the last settlements shows this wagging tail characteristic, which no longer obeys the fractal law. In general, most of the clusters were located below the fitted curve, and there is a gap between the actual and theoretical values of the size distribution.

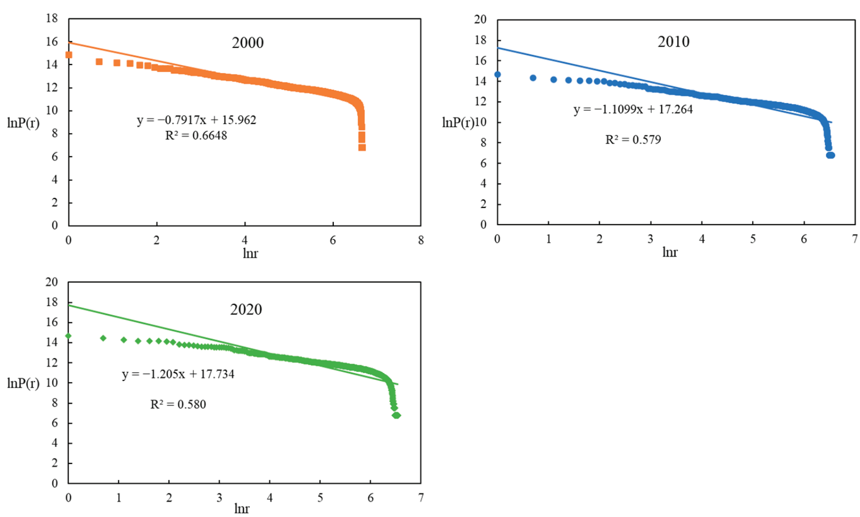

Figure 3. Double logarithmic coordinate map of settlement size distribution.

Over the past 20 years, as a result of a series of land policies, the development of township industrial parks and scenic areas, the transformation of old living areas, and the improvement of transportation facilities, a large number of rural settlements in Changshu have either been expropriated and demolished to live in industrial communities and new rural communities, or have been effectively guided to integrate into towns and cities for community−based development [91]. The built-up areas of towns have expanded and have been optimally reconfigured to some extent. However, to achieve the multi−stage goal of rural revitalization and urban–rural integration, there is still a need to improve quality and efficiency, as the existing scale structure of rural settlements still has the problem that the development of high−order settlements is not prominent. There is more room for improvement, and more middle− and lower−order sporadic rural settlements should be curbed and optimally reconstructed.

4.1.3. Characteristics of the Evolution of the Spatial Agglomeration of Rural Settlement Sizes

Globally, the spatial agglomeration of the size distribution of rural settlements in Changshu has gradually increased over the past 20 years, with Moran's I values gradually increased and confidence levels significantly improved. Moran's I values were calculated to be 0.015374, 0.025438, 0.065632, p−values of 0.171199, 0.080421, 0.000006, and z−values of 1.368363, 1.748251, 4.537884 for the 2000, 2010 and 2020 settlement sizes, respectively. These results showed that in 2000, the Moran's I value was close to zero, failing the 90% confidence test, indicating that the size of rural settlements in Changshu showed a spatially random distribution and there was no significant spatial autocorrelation. In 2010 and 2020, it passed the 90% and 99% confidence tests, respectively, and the Moran's I value is greater than 0, indicating that the scale of rural settlements at this time shows a trend of agglomeration with spatial autocorrelation. However, the maximum Moran's I value is only about 0.1, and the agglomeration was slightly weak.

Locally, there were significant spatial differences in the scale distribution of rural settlements in Changshu, with a narrow range of coldspots and hotspots and a wide range of transitional areas. Between 2000 and 2020, the location of coldspots and hotspots shifted significantly, with a general trend of shifting from south to north (Figure 4). In 2000, the hot spots and sub−hot spots were concentrated in the east of Yushan Town, the middle and west of Guli Town, and the northwest of Bixi Town, because these areas were adjacent to lakes and the Yangtze River, with flat terrain, sufficient water, abundant paddy and dryland resources, and unique hydrothermal conditions suitable for living and agricultural production. The cold spots and sub−cold spots are concentrated in the northern part of Xinzhuang Town and the southwestern part of Yushan Town. There are also natural lakes and river canals in this area. The rural settlements have obvious distribution characteristics near water and cluster on both sides of river canals. However, the scale of settlements was small, and the formation and distribution of settlements in this period were dominated by natural factors. In 2010, the original hot spots and sub-hot spots had disappeared and been expanded into urban built−up areas. The hot spots and sub−hot spots were transferred to the south of Haiyu Town, the southeast of Guli Town and west of the center of Xinzhuang Town. Affected by the development of the township industrial economy, convenient transportation, land policy and agricultural scale [92], the geographical characteristics and scale of rural settlements in these areas have changed due to the concentration of population, capital and other factors. The cold spot area and sub−cold spot area have been transferred to the northwest of Haiyu Town, the northwest of Meili Town and the junction with Bixi Town. In the 10 years from 2000 to 2010, the scope of the urban built-up area of Meili Town has expanded northward, and a large number of small rural settlements have been added to the north and east of the urban built–up area. In 2020, the spatial distribution of coldspots and hotspots differed from the 2010 pattern, with a slight expansion of the original coldspots and hotspot area, the disappearance of the Xinzhuang Town hotspot area, the emergence of new secondary hotspots at the junction of Meili, Bixi and Dongbang Towns, and the approach of the Guli Town hotspot to the town center.

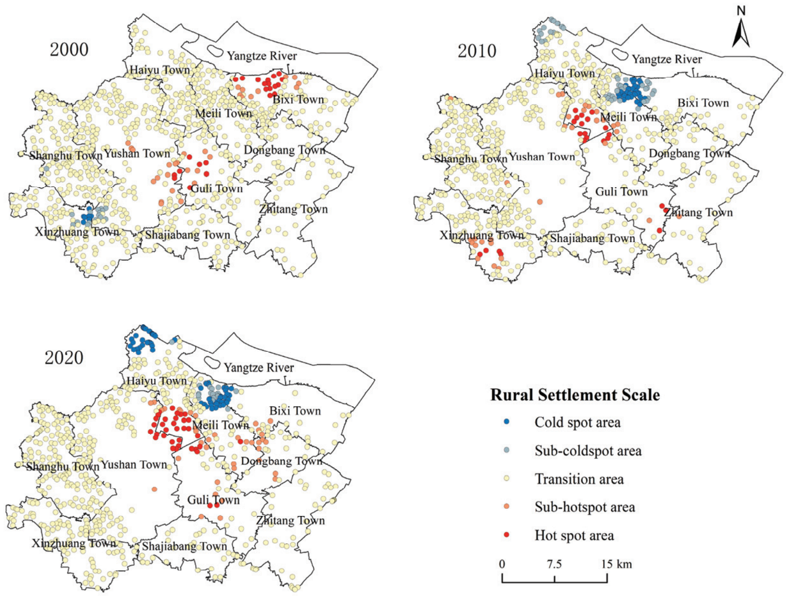

Figure 4. Hot Spot Map of rural settlement scale differentiation in Changshu.

In summary, the spatial pattern of rural settlement size in Changshu corresponds to its hierarchical structure, with small– and medium–scale settlements being widespread and randomly distributed. A comparison with the density map of rural settlements shows a spatial distribution pattern of high-density small–scale, high-density large–scale and low–density large-scale clustering in rural settlements. This indicates that there is still considerable potential for optimizing and reconfiguring the rural settlements in Changshu.

4.2. Optimization of Spatial Structure of Rural Settlements in Changshu

As the "tail of the city and the head of the countryside," small towns connect cities and villages and are an important hub for the integrated development of urban and rural areas [93]. Their development has a particular concentration and radiation capacity for the surrounding settlement areas. The field strength model was used to measure the radiation range of the interaction between villages and towns, to scientifically identify the rural revitalization pole, define the spatial field of villages and towns, divide the rural development areas, support the basic urban and rural network, understand the construction pattern of Changshu villages and towns, and then promote the realization of the multi-level "pole–field–zone–network" goal of rural revitalization.

4.2.1. Rural Revitalization Pole Identification under Township Impact Measurement

Rural influence is a quantitative evaluation of the economic and social development status of rural towns. The results were used as the basis for identifying rural revitalization poles and were arranged into four classes based on the natural break method. Based on the actual development of the townships and following the principle of accessibility, 11 indicators were selected to reflect the development impact of Changshu townships (Table 1) [61,94]. The entropy method [95] was used to determine the index weight and measure the level of town influence (Table 2). As Yushan Town and Bixi Town have been re-designated as streets by the end of 2020, no data were available for each street. Therefore, the scope of this part of the study was set at the eight townships of Meili, Haiyu, Guli, Shajiabang, Zhitang, Dongbang, Xinzhuang and Shanghu. Yushan is the economic, political, cultural and financial center of Changshu, while Bixi is the sub-center of Changshu and the location of Changshu Port and the Changshu Economic Development Zone. Both have absolute advantages in terms of location, economy, transportation and policies compared to other townships, and their development influence is relatively high.

Table 1. Township Impact Measurement Indicator System.

Guideline Level	Indicator Level	Indicator Interpretation	Weight
Comprehensive Economy	GDP of townships (million yuan)	Reflecting the comprehensive economic strength of the township.	0.057
Government Finance	Total financial revenue (million yuan)	Reflecting the financial strength of the township government.	0.067
	General public budget revenue (million yuan)	Reflecting the level of disposable financial resources of the township government and the state of regional enterprises, economic performance, and consumer sentiment.	0.078
Population Size	Total population (persons)	Reflecting the population base and development potential.	0.085
Land Scale	Township built-up area (km^2)	Reflecting the agglomeration scale and attraction of township construction land.	0.199
	Cultivated area (hectare)	Reflecting the base of agricultural development and the capacity of agricultural production factors to cluster.	0.114
Industrial Development	Number of township enterprises (pcs)	Reflecting the development of non-agricultural industries and the ability of the township to absorb non-agricultural employment.	0.083
	Number of industrial enterprises above designated size (pcs)	Reflecting the development of township industry.	0.090
	Township employees (persons)	Reflecting the level of non-farm employment in the townships.	0.079
	Proportion of output value of secondary and tertiary industries in GDP (%)	Reflecting the industrial structure of the township.	0.050
	Number of general shops or supermarkets with a business area of 50 m^2 or more (pcs)	Reflecting the tertiary sector and consumer retail in the township.	0.098

Table 2. Rural Revitalization Pole of Changshu.

Townships	Meili Town	Haiyu Town	Guli Town	Shajiabang Town	Zhitang Town	Dongbang Town	Xinzhuang Town	Shanghu Town
Influence	0.558	0.654	0.743	0.202	0.448	0.048	0.487	0.462
Level	2	1	1	4	3	4	3	3

Note: The levels are classified into 4 classes based on the natural fracture method of ArcGIS 10.5.

In general, the development of the townships in central and northern Changshu was better than that in the south, with the influence showing a spatial pattern of high in the center and low in the east and west. Specifically, Guli Town and Haiyu Town were Level 1 rural revitalization poles, with Guli Town having a developed knitting industry with high concentration, and a fast–developing tertiary industry. Meanwhile, Haiyu was based on building a unique agricultural industry town. Both towns are close to the county capital and have a large scale and a good development foundation. Level 2 Rural Revitalization Pole Meili Township, adjacent to Level 1 Rural Revitalization Pole to the west and Bixi Street to the east, has a township influence of 0.558. Level 3 Rural Revitalization Pole Zhitang Township, Xinzhuang Township, and Shanghu Township, distributed in the periphery of Changshu County, had a comparable township influence. Shajiabang and Dongbang, as 4–level rural revitalization poles, had lower development levels and relatively weaker township influence under the influence of factors such as location conditions, population flow and total economic volume (Table 2).

4.2.2. Spatial Field Definition for Villages and Towns Based on Town Center Accessibility and Tyson Polygons

The Tyson polygon indicates that the distance from any village settlement within a polygon to that town center is less than the distance to town centers within other polygons, reflecting a reasonable range of village spatial fields. The accessibility cost reflects the actual cost of reaching the town center, and to some extent, the actual extent of the village spatial field. The two were spatially superimposed to delineate the spatial radius of different township growth points in Changshu (Figure 5).

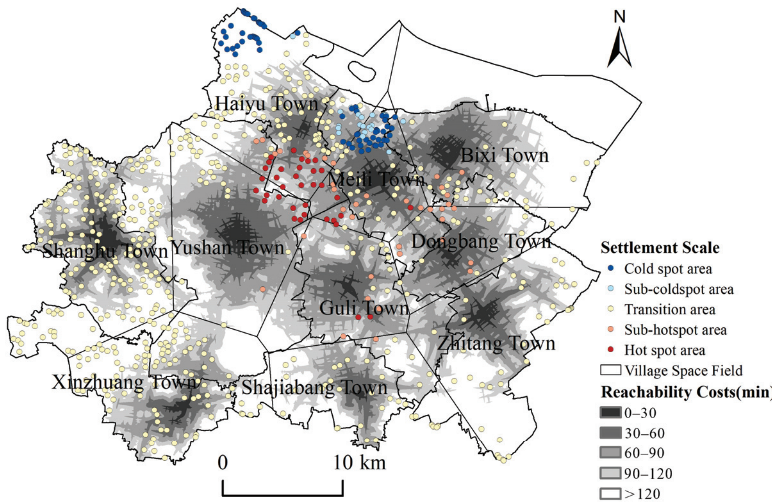

Figure 5. Village space field in Changshu.

We found that: (1) The spatial field extent of the villages and towns did not correspond to the administrative boundaries, but the Tyson polygon tended to be consistent with the accessibility cost results, and the spatial field extent and tendency of each township was more in line with the desired results. (2) The spatial field range of the villages and towns was basically within the one-hour economic circle, with only the north-western part of Xinzhuang, the south–eastern part of Zhitang, Yushan, and the north-western part of Haiyu being within the one-and–a–half–hour economic circle. (3) The spatial field of the villages and towns was generally polycentric and "along the highway," with one–and–a–half–hour economic circle of Haiyu, Meili, Dongbang, Zhitang, Yushan, Guli and Bixi, forming a continuous cluster distribution pattern. (4) There was a clear spatial convergence in the accessibility of some townships, with obvious areas of weak accessibility in the south of Shanghu, the north of Haiyu, the southeast of Zhitang and the east of Bixi. (5) The one–and–a–half hour village spatial fields of the 1, 2, 3 and 4 level village revitalization poles in northeast Changshu were comparable in scope. Although there is a large difference in influence values between townships, convenient transportation and improved infrastructure were conducive to promoting the linked development of village settlements in each township. As the center of the county town, Yushan has a strong ability to reach and radiate, but the spatial field of villages and towns was small and limited to the two–hour economic circle outward from the county town center within the administrative district boundary, as the village settlements there were mostly located in the peripheral areas outside the county town area, while its influence reaches the peripheral areas with difficulty due to the gradient attenuation effect of spatial distance and the substitution effect of the low–grade village revitalization pole. Therefore, the focus and emphasis on promoting rural revitalization in the future can be placed on the 2– and 3–level rural revitalization poles. Rural settlements located within the one-hour economic circle can be identified as a type of community–based development because they are close to the central towns, have a superior location and convenient facilities, have a more concentrated population size, and are advantageous zones for new urbanization development driven by the advantages of township industries, markets and employment [93].

4.2.3. Zone of Rural Development Based on the Rural Hinterland

The rural hinterland based only on the time cost of accessibility was analyzed together with the rural hinterland based on the combined effect of township influence and accessibility costs (Figure 6) to obtain a basic picture of the Changshu Rural Development Zone.

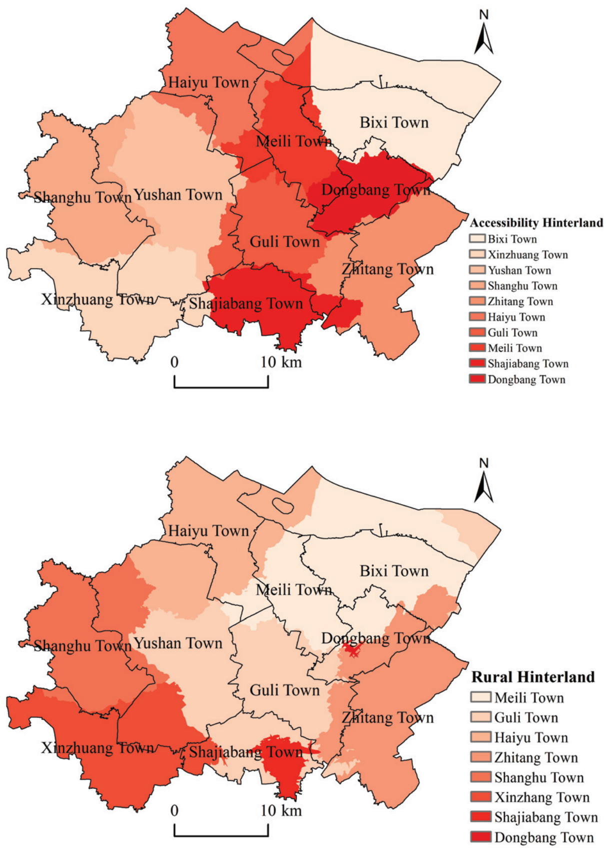

Figure 6. Overlay of Changshu's rural hinterland and administrative boundaries.

The division of the rural hinterland based on accessibility costs showed that the development areas did not correspond to the administrative boundaries and were easily extended to the boundaries of neighboring townships, with the rural development areas of each township nested within each other. The rural development zones of Shanghu, Xinzhang, Zhitang and Bixi not only covered the entire township but also extended to other areas, indicating that their accessibility costs are low and their accessibility is good. The other townships were all locally nested along their borders. In addition, the size of each town's rural development area was generally consistent with the extent of its village spatial field, and the definition of the rural development areas in Shanghu and Xinzhuang are also consistent with development realities, with appropriate reductions and expansions based on accessibility costs.

The division of the rural hinterland based on the field strength model showed that its basic characteristics were consistent with those based on accessibility costs and only change in the hinterland scope. Specifically, Guli, Haiyu and Meili had the widest range of rural development zones as Level 1 and 2 rural revitalization poles, while Dongbang and Shajiabang had significantly reduced ranges of rural development zones because of their low level of influence compared to other townships and their relatively weak development drive on rural settlements in the surrounding areas. The scope of the rural development zones of Shanghu, Xinzhuang and Zhitang, the Level 3 rural revitalization poles, remains basically the same as the scope of the rural development zones based on accessibility costs, even expanding slightly. Although their township influence is at a medium level, the accessibility costs are relatively low, and the combined effect of the two results in larger rural development zones.

There follows the classification of types of rural settlement layout optimization under Rural Development Area. First, the scattered settlement patches within the Tyson polygon and one-hour economic circle of the county town and Bixi Street, which do not have significant scale agglomeration characteristics, should be set up as county urbanization demand-attracting types. Community development should be achieved through the central town drive. Second, clusters with high– or low–value aggregation within the rural development zones of the Level 1 and 2 rural revitalization poles and rural clusters within the one–hour economic circle of other townships should be set up as central township development potential types, strongly radiated by the township center and guaranteed the necessary land for in-situ urbanization development. They are the key targets for rural revitalization. Third, some rural settlements outside the one-hour economic circle and within the two–hour economic circle, relying on the development of various industries, sightseeing, agriculture, horticulture, e-commerce, and other specific industries, can be set up as special functional advantage development keeping types. Finally, regarding the scattered settlements outside the two–hour economic circle of each township in the marginal areas, although they are still in the hinterland, the radiation influence they can receive is weak. Measures such as relocation or settlement reconstruction can be offered to achieve concentrated living, thereby optimizing the intensive use of land. These settlements are the scattered relocation and support types.

4.2.4. Urban and Rural Infrastructure Network Based on Transport and Basic Public Services Connectivity

In the new development period, new urbanization and rural revitalization are two different means to improve the quality of urban–rural development and promote urban–rural integration. The main focus is on promoting the orderly flow of factors such as population, land, industry, science, education, facilities and policies between urban and rural areas to reshape a new pattern of urban–rural integrated development. The integration of facilities is a vital link. Promoting the gradual extension of urban infrastructure and public service facilities to rural areas to achieve universal sharing can help construct a network of paths for the effective flow of various factors and resources [96]. From 2017 to 2021, 115 urban roads were built or upgraded in Changshu, and all 1039 "cluster" villages had access to graded highways. The three–level bus service system of towns and villages was continuously optimized, and the connectivity between urban and rural areas was further improved. There is a need to accelerate the construction of various infrastructure and public service facilities covering both urban and rural areas, such as electricity, natural gas, waste and sewage treatment, logistics and rural power grids, and realize the integration of basic pension insurance, medical insurance and minimum living security benefits for urban and rural residents. Building a multi-level road network and facility system based on a multi-level rural revitalization pole improves the urban–rural infrastructure network that promotes the integrated development of Changshu's cities and rural areas.

In conclusion, the spatial structure of urban and rural settlements in Changshu is clearly hierarchical. As the center and sub-center of Changshu, there is a clear connection channel between the county seat and the central and western regions, and Bixi connects with the east, and both of them drive the development of Changshu as a whole through organizational linkage. The rural revitalization poles at all levels are the key link between urban and rural areas, consolidating the settlement reconstruction system through horizontal and vertical linkages. Within each township, apart from the central township area, there are sub-township built-up areas in other areas of the township that depend on the development of township industry and special industries. These built-up areas influence the development of rural settlements away from the central township area and those on the fringes of neighboring townships. However, there are still some villages that generally lack young new agricultural operators, are located in marginal areas, have poor living and working conditions, and the "Beautiful Residence of Thousands of Villages" project is not strong in terms of continuity. Therefore, based on the level of influence of the townships, their geographical function, and the size of the settlements, the rural settlements within each Rural Development Area are further divided into county urbanization demand attraction type, central township development potential type, special function advantage development maintenance type and sporadic relocation support type, to promote the reorganization of rural settlements, improve quality and efficiency, achieve the multi-level objectives of rural revitalization and help promote urban–rural integration.

5. Discussion

An orderly and reasonable multi-stage urban–rural spatial structure is conducive to promoting synergistic urban–rural development, and the designation of multiple types of villages based on development conditions is conducive to promoting optimal adjustment of rural functions and layout. In 2021–2025, based on its own characteristics and advantages, Changshu will seize the strategic opportunities of the integration of the Yangtze River Delta and the integration of Shanghai and Suzhou, fully connect with Shanghai and Hangzhou, integrate into the main urban area of Suzhou, and strengthen the effective docking with the Yangtze River Delta urban agglomeration. In order to balance urban and rural development, a four-level urban and rural spatial system of "central city–town–rural community–village" is planned based on functional positioning. The central urban area includes the main urban area and port area, which respectively refer to Yushan and Guli of grade 1 rural revitalization, Bixi and Meili of grade 2 rural revitalization. Based on the comprehensive analysis of village development conditions and potential, the current situation of the village is divided into five types: agglomeration promotion, characteristic protection, suburban integration, relocation and removal, and other general categories. However, due to different functional positioning and development conditions, the classification types of village layout in each town are different. For example, Haiyu Town, which is functioned as a new material industry base in the Yangtze River Delta and a service center in the northwest of the city, is divided into four types of integrated villages, city–level controlled villages, tow–level controlled villages and comprehensive regulated villages in the comprehensive renovation planning. Dongbang Town, which functions as a key transportation town in the east of the city and a modern comprehensive town featuring emerging industries, classifies all villages in the town into two categories: renovation type and replacement type.

The multi-stage spatial structure revealed in this study corresponds to the development plan of Changshu city, and the village types were also delineated to promote the optimization of rural settlement layout, attracted by the county urbanization demand attraction type, central township development potential type, special function advantage development maintenance type and sporadic relocation support type. However, only accessibility and township influence were considered in this demarcation, and functional orientation and development conditions were not considered. Therefore, the village types were different from the reality, and the differences between towns were not emphasized. Future research should fully consider the functional orientation and development characteristics of each township, combine with the reality of rural development, formulate differentiated development guidance and further analyze the evolutionary mechanism of the rural settlement system. In addition, due to the limitation of data acquisition, facilities level was not included in the measurement of township influence. In the next research, field survey, semi-structured interview and other methods can be adopted to collect relevant data and supplement the case studies at the village scale. With typical villages, with cluster promotion, suburban integration, characteristic protection and relocation and merger as the entry points, specific optimization plans can be formulated to expand the policy application value of the research results.

6. Conclusions

This paper explored the spatial and temporal evolution characteristics of the rural settlement system in Changshu over the past 20 years from 2000 to 2020, using GIS spatial analysis, fractal dimension and the field strength model, and the spatial structure of rural settlement development in economically developed areas was revealed based on the multi-stage objective of "pole–field–zone–network". The measurement of the evolution of the settlement pattern and the settlement optimization model to construct the village hierarchy and identify the growth pole with the help of the field strength model can, to some extent, provide a research basis and reference for formulating a reasonable spatial hierarchy system of towns and villages at the county level and village consolidation planning. The main conclusions of the study are presented below.

The evolution of the spatial distribution pattern and scale structure system of rural settlements in Changshu City experienced two periods of drastic change and stable adjustment. Now, it is still in the latter period. In order to achieve the goal of rural revitalization, Changshu continues to optimize the village layout, renovate the village environment, and formulate a comprehensive village renovation plan to adjust the structure and layout of rural settlements. The density distribution of rural settlements in Changshu generally shows a spatial pattern of dense in the north and sparse in the south, dense in the east and sparse in the west. The number of rural settlements per unit area is increasing and tending to cluster. The scale structure of rural settlements in Changshu city changed from centralization to dispersion, with the polarization of the scale system of rural settlements enhanced and the gap between the scale of the first and last settlements increased. This has something to do with carrying out the project of "a thousand beautiful villages" and delineating the development of group–type villages. The actual scale of rural settlements was much lower than the theoretical value, and the small and medium–sized settlements were underdeveloped. The spatial agglomeration of settlement size distribution gradually increased, and the location of hot and cold areas shifted from south to north. However, the agglomeration area was relatively small, and the transition area was wide, so the optimization of settlement structure layout still had certain adjustment potential.

The multi-stage objective system of "pole–field–zone–network" constructed against the goal of rural revitalization is helpful to promote the optimization of rural settlement layout in Changshu City, and promote the construction of a reasonable urban–rural network structure. The influence of towns in the middle and north of Changshu is higher than that in the south, with a distinct hierarchy of rural revitalization poles. The spatial extent and development trends of the villages and towns are in line with the desired results, with the areas basically within a two-hour economic circle, showing a polycentric circle pattern and a "roadside" pattern. The size of rural development areas based on hinterland delineation corresponds to the extent of village spatial fields and does not correspond to administrative boundaries, nesting and influencing each other spatially. The urban–rural infrastructure network, built on transport and basic public service links, has become the link between the orderly flow of urban and rural factors. Guided by the importance of rural revitalization, with the spatial field of villages and towns and the rural development area as the role field, under the linkage of the urban–rural foundation network, the county city and Bixi sub-center bear the east and enlighten the west, promoting the orderly development of the county city urbanization demand–attracting type, the central township development potential type, the special functional advantage development maintaining type, and the sporadic relocation and support type villages, thereby realizing multi–level linkage of the whole area urban–rural integration, in line with the actual development of rural settlements in economically developed areas.

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Spatial Patterns of Tourist Attractions in the Yangtze River Delta Region

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Abstract: Tourism is distinctly regional with respect to the regional distribution of tourism resources, tourist attractions and supply, and spatial continuity of tourist activities. Using point-of-interest data from 2166 tourist attractions in the Yangtze River Delta, this study analyzes the spatial distribution pattern of tourist attractions and their influencing factors by applying the methods of nearest proximity index, kernel density analysis, standard deviation ellipse, hotspot analysis, and spatial superposition analysis. The results show that the number of modern recreational tourist attractions accounts for the largest proportion. The spatial distribution pattern shows more attractions in the north than the south and more in the east than the west. The spatial density of tourist attractions in Shanghai is far greater than that in other regions, followed by Jiangsu and Zhejiang. The five types of tourist attractions show a significant aggregation state. Natural ecological tourist attractions are clustered near Nanjing and Huangshan; historical and cultural tourist attractions are formed in a T-shape by Shanghai, Hangzhou, and Nanjing; modern recreational tourist attractions are clustered in Shanghai and Hangzhou; and industrial integration tourist attractions are clustered in Shanghai, Nanjing, and Hangzhou. Physical geography, traffic, and social economy are the main factors affecting the spatial distribution of tourist attractions.

Keywords: spatial patterns; tourist attraction; GIS; Yangtze River Delta

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1. Introduction

Tourist attractions act as gathering places to display tourism resources and are the core and location of tourism activities [1]. Tourist attractions can be scenic spots, nature reserves, cultural museums, tourist resorts, geoparks, etc. They have functions for visiting, leisure/vacation, recreation, and fitness [2]. Therefore, many scholars have explored and analyzed the classification of tourist attractions. For example, Pearce et al. divided tourist attractions into two categories, namely, natural and human-made [3]. This classification is similar to the classification of tourism resources and shows that tourist attractions commonly have integrated elements that are natural and human-made and cannot be separated completely, especially tourist attractions with both natural and cultural heritage. Leask classified tourist attractions according to the natural or human-made, paid or free, public or private, local or regional market, and domestic or international market [4]. However, he did not propose the names of various tourist attractions, only the classification criteria. Lew pointed out that most studies basically have classified tourist attractions from three perspectives, namely, ideographic, structural, and tourist cognition perspectives [1]. However, regardless of the type of tourist attractions, their goal is to provide tourists with a comfortable travel experience and to achieve the social, economic, and environmentally sustainable development of tourist attractions [2].

Tourist attractions are a very general concept and generally refer to a number of geographically connected places with a number of common characteristics, including transportation networks and tourism service facilities composed of regional units [2]. Its interior has the characteristics of consistency, relevance, and integrity. It can be restricted by the administrative region but also can break through the constraints of the administrative region based on landform, landscape, social and cultural relations, and economic relations [5]. Its spatial span varies greatly, from as large as a country to as small as a village. Although there is no definition that applies to all tourist attractions, all tourist attractions have the following basic characteristics. First, they are located in a region with a clear geographical scope. Second, they are based on tourism resources. Third, they are places for engaging in tourism and leisure activities.

The spatial pattern of tourist attractions not only involves the distribution state and element combination of tourist attractions but also has a significant impact on the spatial behavior of tourists [6,7]. For example, Pan et al. analyzed the spatial distribution characteristics of 2424 A-level tourist attractions in China based on methods such as the nearest neighbor index, K-index, and hotspot clustering in GIS. Furthermore, the spatial distribution of tourist attractions has a significant impact on the spatial and temporal behavior of tourists, regional tourism income, and social development level. Previous studies on the spatial structure of tourism mainly used location theory, central periphery theory, and the core edge model to explore the spatial structure and the evolution process of tourism destinations [8,9]. However, there are few studies on the spatial pattern of tourist attractions, which mainly focus on the spatial distribution characteristics of tourist attractions [10,11], influencing factors [12,13], spatio-temporal evolution [14], and optimal path [15]. For example, Kang et al. analyzed the spatial structure of the tourist attraction system in Seoul, South Korea, using a geographic information system based on anchor point theory [16]. Based on the data of high-level tourist attractions in Inner Mongolia, China, Wu et al. systematically sorted out the spatial distribution pattern, accessibility, and influencing factors of various tourist attractions by using methods such as nearest neighbor index, kernel density, accessibility, and spatial autocorrelation [17].

The research objects of previous studies are mostly A-level tourist attractions. Recently, some scholars have conducted classification research for all tourist attractions in the region, using mathematical statistics and spatial analysis as the main research methods. For example, Guo et al. took all tourist attractions in Shanxi Province, China as the research object. Based on their classification, they studied the spatial distribution pattern, distribution direction, and spatial distribution characteristics of different categories of tourist attractions based on GIS analysis technology [18]. In addition, Matthews et al. pointed out that the superposition of two or more attractions creates a cumulative attraction, which can provide a critical mass that cannot be provided by individual attractions and is essential for attracting tourists [19]. Wang et al. further analyzed the spatial structure of tourist attraction's cooperation in the Yangtze River Delta of China by using geographic information systems and social network analysis methods [11]. Therefore, it is of great practical significance to study the spatial pattern of tourist attractions and their influencing factors.

Although some scholars have found that the size of regional tourism attractions is closely related to the degree of spatial agglomeration of tourist attractions [20–30], the previous research objects of the spatial distribution of tourist attractions were mostly A-level tourist attractions, and there was a lack of research on the spatial distribution of all existing tourist attractions after systematic sorting and classification. Few studies have focused on the spatial patterns of tourist attractions in geographically similar and culturally similar regions (such as the Yangtze River Delta). In particular, the tourist attractions in the Yangtze River Delta region of China, due to their small differences in tourism resource endowments and similar types, have more intense competition among themselves and greater internal friction. In addition, using big data and traditional geographic information systems to study the spatial pattern of tourist attractions in the Yangtze River Delta region is even rarer. To fill this research gap, this study first classified the tourist attractions in the

Yangtze River Delta region, and then studied the spatial distribution pattern, distribution direction, and influencing factors of tourist attractions based on point-of-interest (POI) data. The research questions of this study are as follows. What categories can tourist attractions be divided into? What is the spatial pattern of different types of tourist attractions? Are there spatial differences? If there are spatial differences, what are the influencing factors? These issues reflect the spatial structure and spatial distribution of tourist attractions. It is of great significance to understand the spatial organization and attractiveness of tourist attractions for the purpose of policymaking for tourism spatial planning. To answer these questions, we established three sub-goals.

First, based on previous studies, this study uses ArcMap 10.7 software to analyze the spatial pattern of tourist attractions using the methods of average nearest neighbor (ANN) analysis, kernel density analysis, standard deviational ellipse, and hot spot analysis.

Second, the main factors affecting the spatial pattern of tourist attractions are clarified by using spatial superposition analysis from the three aspects of physical geography, location and transportation, and social economy.

Third, this study provides a basis for clarifying the advantageous tourism resources of cities and finding the growth poles of tourist attractions. It also provides a reference for the rational development of tourism resources, the orientation of tourism development, and the corresponding tourism marketing strategies.

2. Materials and Methods

2.1. Study Area

The Yangtze River Delta region is referred to as the Yangtze River Delta. There are 41 cities, including Shanghai, Jiangsu, Zhejiang, and Anhui provinces. The Yangtze River Delta is located in the lower reaches of the Yangtze River in China, bordering the Yellow Sea and the East China Sea. It is located at the intersection of the rivers and seas. There are many coastal ports along the river, and it is an alluvial plain formed before the Yangtze River enters the sea. At the end of 2019, the Yangtze River Delta had a population of 227 million, covering an area of 358,000 square kilometers. In 2020, the GDP of the Yangtze River Delta region was 24.5 trillion yuan. The urbanization rate of permanent residents has exceeded 60 percent. With less than 4 percent of China's land area, it has generated nearly one-quarter of China's total economic output and one-third of China's total imports and exports. In 2019, the density of the railway network in the Yangtze River Delta reached 325 km per 10,000 square kilometers, 2.2 times the average level in China.

The Yangtze River Delta is rich in tourism resources and highly developed in tourist attractions, including natural and ecological tourist attractions, such as Huangshan and Taihu Lake; historical and cultural tourist attractions, such as Xidi and Hongcun; and human-made tourist attractions, such as Disneyland and Songcheng. The Yangtze River Delta enjoys high accessibility, with numerous air, high-speed rail, and high-speed stations and a dense road network, with basically seamless connections between various transportation modes. In addition, it has superior accommodation and catering facilities which can meet the needs of different people for entertainment, business, and other aspects. Thus, it is representative to select the tourist attractions in the Yangtze River Delta as a case study.

2.2. Data Collection and Analysis

Gaode Map (Amap) has Grade A surveying and mapping qualification for navigation of electronic Maps, Grade A surveying and mapping aerial photography, and Grade A surveying and mapping qualification for Internet Map service. Moreover, Gaode Map has the characteristics of deep POI, and its data are scientific, real-time, and effective. Therefore, this study extracted 3533 POI data points from Gaode Map on 19 March 2022. Cities in the Yangtze River Delta were selected as the selected region, and three keywords of "tourism", "tourist attraction", and "scenic spot" were entered. The attributes of POI data points included city, name, address, longitude and latitude coordinates, and other information. The POI extraction process contained the keywords related to "tourism" in the data points, such as "hotel" and "tourist hotels". As tourist attractions are the research object, this study is not related to other parts of the travel service industry. Thus, after eliminating duplicate data and "tourist hotels" where the research object is not based on POI data, we retained a total of 2166 POI data. POI data are points of interest on a map. POI data belongs to the category of geospatial big data, which represents the point-like spatial data of real geographic entities, generally including name, category, geographic coordinates, and other information. Due to its low acquisition cost and high data accuracy, POI data can meet the requirements of urban spatial layout planning and has been widely applied in the field of regional planning research, such as urban functional area identification, residents' spatio-temporal behavior, urban structure analysis, natural environment assessment, etc. POI data comes from a wide range of sources. Amap and Baidu Map can provide all kinds of POI data needed for research. Researchers can use Python, Java, and other programming languages to obtain the relevant JSON format data through API, and then extract the required POI data from the JSON data.

2.3. Research Methods

Due to the differences in natural geographical environment, history, economy, culture, and other aspects in different regions of the Yangtze River Delta, the distribution of tourist attractions in the Yangtze River Delta may also be different. In this study, the average nearest neighbor analysis, kernel density, standard deviational ellipse, and hot spot analysis were selected to explore the overall spatial distribution pattern, agglomeration characteristics, distribution direction, and spatial distribution characteristics of specific cities of tourist attractions in the Yangtze River Delta. The spatial pattern of tourist attractions was studied by using the correlation method of global spatial distribution and local spatial distribution in GIS spatial analysis from the whole to the local order. This can also be seen as a consecutive analysis line of spatial analysis.

2.3.1. Average Nearest Neighbor Analysis

ANN analysis measures the distance between the centroid of each element and the centroid of its nearest neighbor. It then computes the average of all those nearest neighbor distances. The ANN is calculated by dividing the observed average distance by the expected average distance. The ANN can be calculated by

$$ANN = \frac{\overline{D}_O}{\overline{D}_E} \tag{1}$$

In Formula (1), $\overline{D}_O$ is the average of the distance between the measuring element and its nearest neighbor element centroid and $\overline{D}_E$ is the average distance of the random distribution of factors. If ANN is greater than 1, it is a random distribution; if ANN is less than 1, it is an agglomeration distribution.

2.3.2. Kernel Density

We applied kernel density to analyze the spatial density of tourist attractions [8], and its formula is as follows:

$$f_n(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x - x_i}{h}\right) \tag{2}$$

In Formula (2), x is the longitude and latitude position shown in the POI data of tourist attractions, x_i is the tourist attractions formed with x as the center of the circle and h as the radius, and the number of them is n.

2.3.3. Standard Deviational Ellipse

The standard deviational ellipse in the spatial analysis was first proposed by Lefever in 1926 [31]. We used this method to analyze the direction of the spatial distribution of tourist attractions. First, we determined the center of the circle. We directly used the arithmetic mean center to calculate the center of the ellipse. The formula is as follows:

$$SDE_x = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \overline{X}\right)^2}{n}} \tag{3}$$

$$SDE_y = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \overline{Y}\right)^2}{n}} \tag{4}$$

In Formulas (3) and (4), x_i and y_i are the spatial position coordinates of each element, and X and Y are the arithmetic mean centers. SDE_x and SDE_y are the center of the ellipse.

Then, we took the X axis as the criterion; due north (12 points direction) is 0 degrees, with clockwise rotation to determine the direction. The calculation formula is as follows:

$$\tan\theta = \frac{A+B}{C} \tag{5}$$

$$A = \left(\sum_{i=1}^{n}\widetilde{x}_i^2 - \sum_{i=1}^{n}\widetilde{y}_i^2\right) \tag{6}$$

$$B = \sqrt{\left(\sum_{i=1}^{n}\widetilde{x}_i^2 - \sum_{i=1}^{n}\widetilde{y}_i^2\right)^2 + 4\left(\sum_{i=1}^{n}\widetilde{x}_i\widetilde{y}_i\right)^2} \tag{7}$$

$$C = 2\sum_{i=1}^{n}\widetilde{x}_i\widetilde{y}_i \tag{8}$$

In Formulas (6)–(8), x_i and y_i are the difference between the average center and the x and y coordinates. Finally, we determined the length of the X-axis and Y-axis as follows:

$$\sigma_x = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{n}\left(\widetilde{x}_i\cos\theta - \widetilde{y}_i\sin\theta\right)^2}{n}} \tag{9}$$

$$\sigma_y = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{n}\left(\widetilde{x}_i\sin\theta + \widetilde{y}_i\cos\theta\right)^2}{n}} \tag{10}$$

2.3.4. Hot Spot Analysis

We used hot spot analysis to identify spatially significant hot and cold spots by using the local General G index given a set of weighted elements. Getis-Ord G_i^* was utilized to analyze the identification of hot spots. The formula is as follows:

$$G_i^*(d) = \sum_{j=1}^{n}W_{ij}(d)X_j / \sum_{j=1}^{n}X_j \tag{11}$$

In Formula (11), $W_{ij}(d)$ represents the impact degree of individual i to individual j in space, X_j is the attribute value of the location j. Further standardization of G_i^* leads to the following formula:

$$Z(G_i^*) = [G_i^* - E(G_i^*)]/\sqrt{Var\left(G_i^*\right)} \tag{12}$$

In Formula (12): $E\left(G_i^*\right)$ and $Var\left(G_i^*\right)$ are the matrix of expectation and variance, respectively. When it shows statistical significance, if $Z\left(G_i^*\right)$ scores over 0, the higher the score, the denser the high-value clustering of target object attributes (to form hot spots); when $Z\left(G_i^*\right)$ scores below 0, the lower the score, the denser the low-value clustering of target object attributes (to form cold spots) [18]. Hot spot analysis checks every element in the environment of neighboring elements. Therefore, a single element and its surrounding are all high values; that is, the area is a gathering area of high values with high values, which is called a hot spot. On the contrary, the cold spot indicates not only the low value itself but also the low value adjacent to it, that is, the aggregation area of low value and low value. We applied this method to analyze the spatial agglomeration of tourist attractions.

3. Spatial Patterns of Tourist Attractions

3.1. Classification of Tourist Attractions

Most previous research on the classification of tourist attractions refers to the classification method of tourist resources, but there are some essential differences between tourist resources and tourist attractions. Tourism resources [22] are the elements that attract tourists to visit tourist destinations and are the basis of tourism product development, while tourist attractions [23] are the product of the market-oriented development of tourism resources and the main body of tourism destination marketing. Therefore, this study refers to the classification standards in "The Development Report of China's Tourist Attractions (2019–2020) Fact Sheet" published by the Ministry of Culture and Tourism of China and divides the tourist attractions in the Yangtze River Delta into five categories: natural ecological tourist attractions, historical and cultural tourist attractions, modern recreational tourist attractions, industrial integration of tourist attractions, and other kinds of tourist attractions (Table 1).

Table 1. Types of tourist attractions in the Yangtze River Delta.

Categories	Quantity	Examples of Tourist Attractions
Natural ecological tourist attractions	404	Huangshan Scenic Area
Historical and cultural tourist attractions	598	Mr. Chiang Kai-shek's former residence
Modern recreational tourist attractions	951	Shanghai Disney Resort
Industrial integration of tourist attractions	190	CCTV Wuxi Studios
Other kinds of tourist attractions	23	Shanghai Tower

Among them, natural ecological tourist attractions refer to scenic attractions based on natural ecological tourism resources (including forests, waters, geology, landforms, etc.). Historical and cultural tourist attractions refer to the attractions based on various historical and cultural tourist resources (including ancient villages, war sites, museums, etc.), such as cultural relics, arts, social environment, ethnic customs, and material production. Modern recreational tourist attractions refer to a recreational area that relies on a variety of recreational activities, elements, services, and reception facilities, including theme parks, resorts, rural areas, urban parks, and characteristic streets. Industrial integration of tourist attractions refers to tourist attractions that are formed based on the intercrossing, interpenetration, and gradual integration of tourism and other different industrial categories (including industrial tourism, science and technology education tourism, cultural and creative tourism, etc.). Other kinds of tourist attractions refer to tourist attractions (specifically buildings, sculptures, etc.) that cannot be counted among the above kinds of tourist attractions.

In the division of tourist attractions, if we found mixed tourist attractions, we will first judge what kind of tourism resources occupy the dominant position and classify tourist attractions according to the tourism resources [1–18]. However, there are also exceptions, such as some different types of tourism resources in the same tourist attraction that obviously belong to different functional areas. In this case, we prefer to break it down. For example, the Huangshan Scenic Area belongs to natural ecological tourist attractions and the Huangshan Resort belongs to modern recreational attractions. Therefore, Huangshan Scenic Area and Huangshan Resort are regarded as two independent tourist attractions.

The number of various tourist attractions in descending order is modern recreational tourist attractions, historical and cultural tourist attractions, natural ecological tourist attractions, industrial integration tourist attractions, and other kinds of tourist attractions, indicating that the marketization degree of tourist attractions is relatively high, and their tourist products tend to be diversified. The number of modern recreational tourist attractions has far exceeded other types of tourist attractions, indicating that the development of modern human-made tourist attractions is more in-depth. The number of historical and cultural tourist attractions ranked second, indicating that the Yangtze River Delta is rich in cultural tourism resources, including Nanjing, the ancient capital of the six Dynasties, Shanghai, Anhui, famous for its ancient villages in southern Anhui, and Zhejiang, represented by various neolithic sites, official kiln sites, and overseas Chinese hometown culture. The number of natural ecological tourist attractions is the third, mainly because the Yangtze River Delta has mountain-type tourism resources, including Zhejiang-Fujian hills, Huangshan and Dabie Mountains, and dispersed river/lake tourism resources. The number of industrial integration tourist attractions ranks fourth, which reflects the level of economic development and modernization of the Yangtze River Delta region. However, due to the lack of a deep foundation and large investment, there is still a gap between their number and the top three tourist attractions. The number of other kinds of tourist attractions ranked fifth, mainly as a small number of tourist attractions that could not be classified into the specific types mentioned above.

Arcmap10.7 software was used to visually express the types of tourist attractions (Figure 1). The vector map data of administrative boundaries were obtained from the Database of the China National Basic Geographic Information System. The five types of tourist attractions mentioned above are distributed in all cities of the Yangtze River Delta, but there are spatial differences in the quantity distribution of the five types of tourist attractions. The number of tourist attractions presents a spatial distribution pattern of more in the north than the south and more in the east than the west.

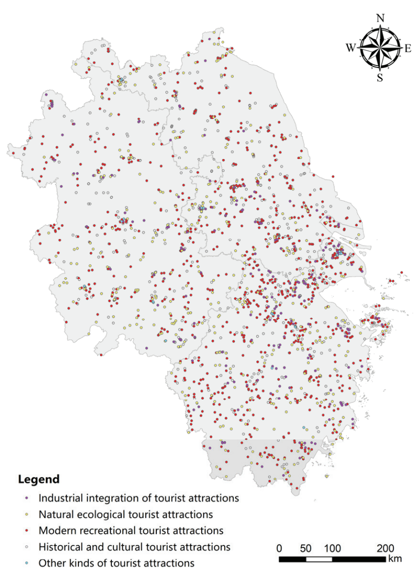

Figure 1. Spatial layout of different types of tourist attractions.

From the spatial density of tourist attractions (number of tourist attractions/land area) (Table 2), various tourist attractions in Shanghai space density were significantly greater than in other areas, including the historical and cultural tourist attractions, modern recreational tourist attractions, and industrial integration of tourist attractions; the density of other types of tourist attractions are twice that in other areas. This shows that the tourist attractions in Shanghai have formed a certain agglomeration effect, and their overall competitiveness is greater than that of surrounding areas. By comparing various tourist attractions within the territory of Jiangsu, Zhejiang, and Anhui number, we can find that historical and cultural tourist attractions in Jiangsu and Zhejiang natural ecological tourist attractions, modern recreational tourist attractions, and industrial integration of tourist attractions density have a certain comparative advantage, while the density of various kinds of tourist attractions in Anhui province is relatively low.

Table 2. The density of the five types of tourist attractions (per 10,000 km^2).

Region	Categories				
	Natural Ecological Tourist Attractions	Historical and Cultural Tourist Attractions	Modern Recreational Tourist Attractions	Industrial Integration of Tourist Attractions	Other Kinds of Tourist Attractions
Shanghai	17.350	52.050	104.101	28.391	12.618
Jiangsu	9.795	21.082	23.134	3.358	0.373
Zhejiang	14.408	14.976	37.062	8.910	0.474
Anhui	9.707	12.919	17.559	2.998	0.428

3.2. Average Nearest Neighbor Analysis

The ANN analysis tool in the spatial statistics toolbar of ArcMap 10.7 software was used to analyze the five categories of tourist attractions and their overall agglomeration effect, and the ANN index of tourist attractions was obtained (Table 3).

Table 3. Results of average nearest neighbor analysis of tourist attractions.

Categories	*ANN*	Z	P
Natural ecological tourist attractions	0.79	−7.90	0
Historical and cultural tourist attractions	0.64	−16.60	0
Modern recreational tourist attractions	0.73	−16.06	0
Industrial integration of tourist attractions	0.71	−7.55	0
Other kinds of tourist attractions	0.47	−4.90	0.01
The general situation without classification	0.66	−30.39	0

The ANN values of the five types of tourist attractions and their general situation are all less than 1, and the Z value of the general situation is −30.39, indicating that both the overall distribution of tourist attractions and their spatial distribution of various types present a state of significant agglomeration. This may be due to the rich and dense spatial distribution of tourism resources, resulting in similar spatial characteristics of tourist attractions.

3.3. Kernel Density Analysis

Using kernel density analysis in the spatial analysis toolbar of ArcMap 10.7 software, the POI data of five types of tourist attractions were typed, and the results were visualized and derived to obtain the spatial distribution and characteristics of each type of tourist attraction (Figure 2).

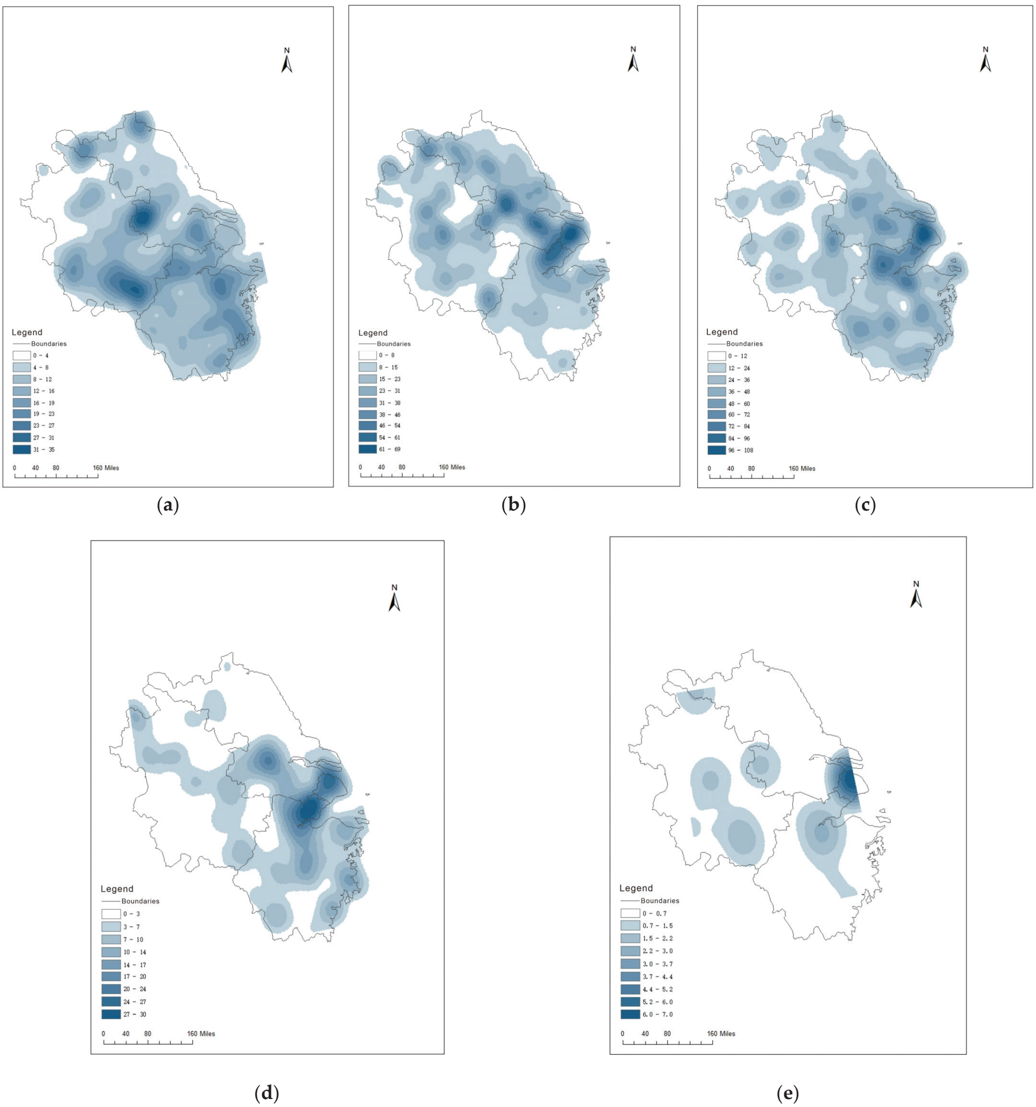

Figure 2. Kernel density of the five types of tourist attractions (**a**) Natural ecological tourist attractions; (**b**) Historical and cultural tourist attractions; (**c**) Modern recreational tourist attractions; (**d**) Industrial integration of tourist attractions; and (**e**) Other kinds of tourist attractions.

Figure 2a shows that the two areas with the highest kernel density of natural ecological tourist attractions are concentrated near Huangshan City and Nanjing City. In the Nanjing area, there are Jiangxinzhou and the riverside scenic belt formed by the Yangtze River, mountain-type tourist landscapes, such as Zhongshan Mountain and Qixia Mountain, and lake-type tourist landscapes such as Xuanwu Lake, while the high-density area with Huangshan city as the core covers many famous mountains, such as Huangshan Mountain, Jiuhua Mountain, Qiyun Mountain, and Tianzhu Mountain. These tourist attractions have become the main tourist attraction for the area. Around the east side of Taihu Lake, there is a relatively high-density area, which is the tourist landscape of the lakes scattered in the lower reaches of the Yangtze River. The density was lower in northern Anhui, central and northern Jiangsu coastal areas, and the area around Shanghai.

It can be seen from Figure 2b that the high kernel density distribution areas of historical and cultural tourist attractions are concentrated in Shanghai, Hangzhou, Nanjing, and their surrounding areas, which together constitute the T-shaped high-density center. This is because Nanjing is the ancient capital of six dynasties in Chinese history, and its historical and cultural tourism resources are rich. Shanghai and Hangzhou have always been places where scholars, businesspeople, and travelers gather, leaving a lot of historical and cultural tourist resources, such as ancient books and residential sites. Anhui is rich in tourism resources along the Yangtze River and Dabie Mountains, and there are many relics and memorials during the War of Resistance against Japanese Aggression. However, due to the topography of Zhejiang-Fujian Hills, there are few historical and cultural tourism resources in southern Zhejiang, and the density of historical and cultural tourist attractions is also low.

According to the kernel density analysis chart of modern recreational tourist attractions, Shanghai is the area with the highest density. There are not only theme amusement and leisure attractions, represented by Disneyland in the suburbs, within the city, Shanghai Wildlife Park, Laowai Street Scenic Spot, and other parks and special streets cater to the recreational needs of both tourists and citizens, stretching all the way to Zhejiang province. In the northeast of Zhejiang, there is a relatively high-density area, namely, the leisure resort area represented by the Moganshan B&B group. However, the density of most of Anhui and northern Jiangsu is very low, which may be due to the relatively undeveloped economies of these regions and the limited funds for the construction of modern recreational tourist attractions.

The industrial integration of tourist attractions in the kernel density analysis diagram shows that the area near Shanghai, Ningbo, and Hangzhou form a high-density area, largely due to its large number of industry categories, giving it a solid industrial foundation, and leading to the integration of industry, agriculture, and tertiary sectors, which have developed industrial tourism, and other tourist attractions.

Other kinds of tourist attractions are mainly single buildings and sculptures, such as Shanghai Tower. The number of such tourist attractions is small and unevenly distributed. However, Shanghai, Hangzhou, Nanjing, Hefei, and Huangshan and their surrounding areas are relatively high-density areas. Because there is no high-density area, it shows that it has not become a growth pole and is not dominant in the competition of various types of tourist attractions in the Yangtze River Delta.

3.4. Standard Deviation Elliptic Analysis

The standard deviation ellipse in the spatial statistics toolbar of ArcMap 10.7 was used to analyze the spatial distribution direction and trend of tourist attractions (Figure 3). According to the shape of the standard deviation ellipse, the distribution direction of the five types of tourist attractions presents a northwest to southeast trend. Comparing the standard deviation ellipse shapes of the five types of tourist attractions, we see that other kinds of tourist attractions have great differences in standard deviation ellipse shapes, while the other types have little differences.

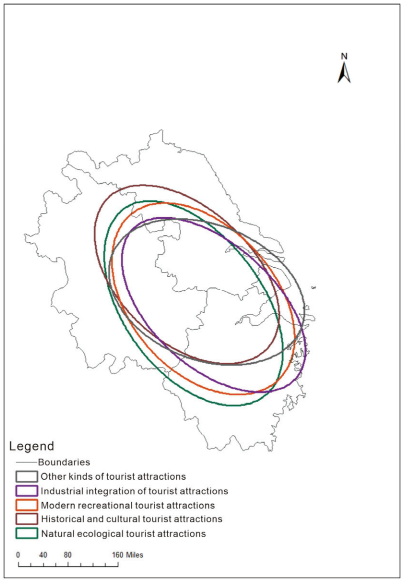

Figure 3. Standard deviation ellipse of the five types of tourist attractions.

The *X*-axis of the ellipse represents the spatial distribution direction of tourist attractions, and the shorter the *X*-axis is, the less obvious the direction is. According to the order from a long to short *X* axis (Table 4), the length of the long half axis of the standard deviation ellipse of the five types of tourist attractions is as follows: industrial integration tourist attractions, historical and cultural tourist attractions, other kinds of tourist attractions, modern recreational tourist attractions, and natural ecological tourist attractions. It is evident that the direction of the spatial distribution of industrial integration tourist attractions is the most obvious, while the direction of the spatial distribution of natural ecological tourist attractions is the least obvious, and the other three types of tourist attractions fall in between. This may be because the industrial integration of tourist attractions can reflect economic development factors and is largely affected by human factors, making its spatial distribution direction the most obvious. Meanwhile, tourism resources in natural ecological tourist attractions are shaped by natural internal forces and external forces, and are natural expressions of topography and landform, making their distribution direction the least obvious.

Table 4. Standard deviation ellipse parameters of the five types of tourist attractions.

Type	The Length of the Major Axis	The Length of the Short Axis	Degree of Angle of Deviation (θ)
Natural ecological tourist attractions	1.806	2.857	145.37
Historical and cultural tourist attractions	2.765	1.618	133.51
Modern recreational tourist attractions	1.87	2.744	138.39
Industrial integration of tourist attractions	2.765	1.574	134.95
Other kinds of tourist attractions	2.686	1.746	113.48

The length of the short half-axis of the ellipse (*Y* axis) represents the centrality of the spatial distribution of tourist attractions and the size of the distribution range. According to the length of the *Y* axis from long to short (Table 4), the length of the standard deviation ellipse short half axis of the five types of tourist attractions is as follows: natural ecological tourist attractions, modern recreation tourist attractions, historical and cultural tourist attractions, other kinds of tourist attractions, and industrial integration tourist attractions. Among them, the centripetal force of natural ecological tourist attractions is the weakest, and its distribution range is the widest. The spatial distribution of industrial integration tourist attractions has a stronger centripetal force and a higher degree of agglomeration.

From the angle of the ellipse (Table 4), the angle of natural ecological tourist attractions, modern recreational tourist attractions, industrial integration tourist attractions, historical and cultural tourist attractions, and other kinds of tourist attractions are between 90 and 180 degrees, showing a northwest to southeast trend, which is consistent with the shape trend of the Yangtze River Delta administrative region. Among them, the deflection angle of natural ecological tourist attractions is the largest, at 145.37°, which is consistent with the terrain trend of Jianghuai Plain, Taihu Plain, and other plains of the lower reaches of the Yangtze River as well as Dabie Mountain, Huangshan Mountain, and other mountains and hills.

3.5. Hot Spot Analysis

Hot spot analysis in clustering distribution mapping in the spatial statistics toolbar of ArcMap 10.7 software was used to obtain hot spot maps of the five types of tourist attractions (Figure 4). In Figure 4, blue represents the cold spot, green represents the sub-cold spot, yellow represents the zero (also known as the transition zone), orange represents the sub-hot spot, and red represents the hot spot. Due to the influence of physical geographical factors, such as the Zhejiang-Fujian hills and Huangshan Mountain, the cold spots and hot spots of natural ecological tourist attractions show a gradual change from south to north. The hot spots appeared in some cities of Zhejiang province in the south, while the cold spots appeared in Fuyang, Bozhou, Bengbu, and other areas in the north of Anhui. The hot spots of historical and cultural tourist attractions appeared in Shanghai and its surrounding areas, and the northern Jiangsu, Lu'an, Hangzhou, Ningbo, and other regions also had high heat, while the cold spots appeared in Lishui and Wenzhou of Zhejiang province. The cold spots and hot spots of modern recreational tourist attractions show an obvious transition change from southeast to northwest. The hot spots appear in Shanghai and most areas of Zhejiang province, while the cold spots appear in northern Anhui and northern Jiangsu. Similar to the distribution characteristics of modern recreational tourist attractions, the industrial integration tourist attractions show a pattern of centering on Shanghai-Hangzhou-Ningbo and expanding outwards in a circle pattern. Hot spots appear in Shanghai-Hangzhou-Ningbo and other regions, while cold spots appear in the northern part of the Yangtze River. The hot spots of other types of tourist attractions appear in Shanghai and surrounding cities, and the zero-point area occupies most of the region without obvious aggregation phenomenon.

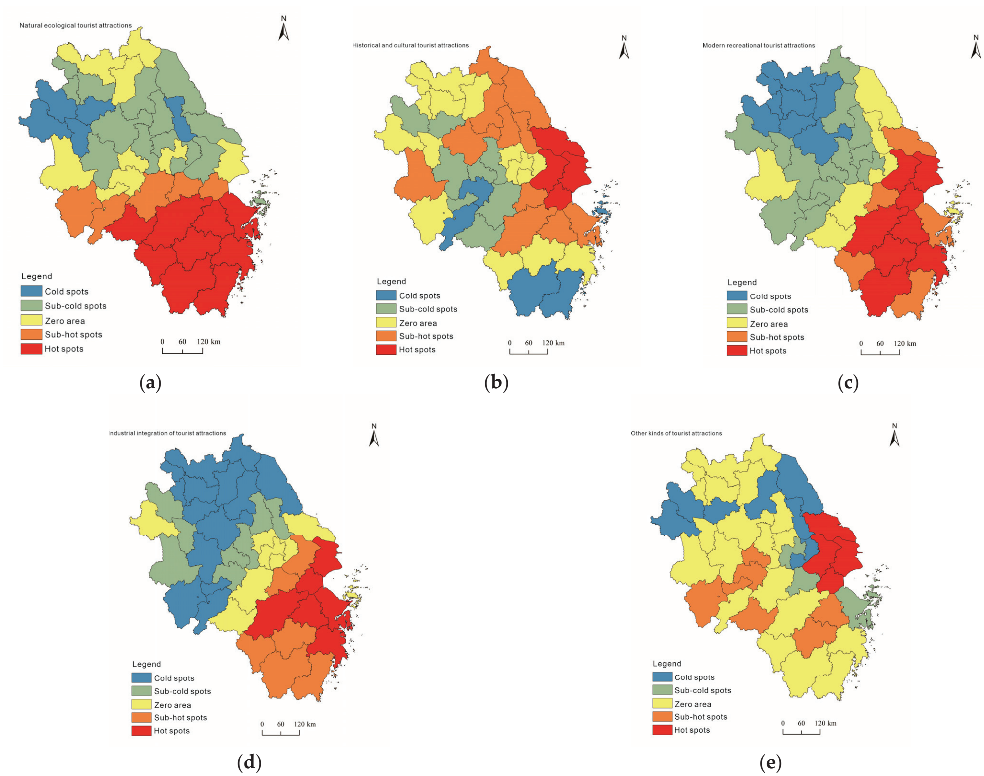

Figure 4. Distribution of hot spots in the five types of tourist attractions: (**a**) Natural ecological tourist attractions; (**b**) Historical and cultural tourist attractions; (**c**) Modern recreational tourist attractions; (**d**) Industrial integration of tourist attractions; and (**e**) Other kinds of tourist attractions.

4. Factors Influencing the Spatial Patterns of Tourist Attractions

The spatial patterns of tourist attractions are comprehensively influenced by different factors [30–45]. Based on previous studies, this study analyzes the influencing factors of the spatial pattern of tourist attractions from the three dimensions of physical geography, social economy, and traffic. Meanwhile, according to the frequency statistics method, the influencing factors with high frequency in previous studies are selected. Natural geographical factors, such as landforms and river systems, are important landscape elements and endogenous factors that affect the spatial patterns of tourist attractions. Good social and economic conditions are the external guarantee for the stable and healthy development of tourist attractions [46–57]. Finally, the connection of the traffic network can effectively connect different types of tourist attractions, form a series of characteristic tourist routes, and promote the reorganization and optimization of the spatial pattern of tourist attractions [20].

4.1. Physical Geographical Factors

4.1.1. Analysis of the Impact of Topography and Landform

Topography is the skeleton of tourist attractions. Undulating topography can increase the sense of spatial hierarchy of tourist landscape and enhance its aesthetic value [46–57]. Different types of landforms can not only form tourist landscapes themselves but also form higher tourist landscapes combined with other elements. Therefore, landform restricts the spatial patterns of tourist attractions.

Figure 5 is obtained by superimposing the elevation layer and the spatial patterns layer in tourist attractions. The elevation is represented by grayscale in the legend of

Figure 5; the larger the grayscale value, the higher the elevation value. As shown in Figure 5, topographically, the overall regional shape of the Yangtze River Delta is northwest to southeast, which determines the consistency of the distribution direction of various tourist attractions, namely, the northwest to southeast distribution. The Yangtze River Delta is characterized by high terrain in the southwest and low terrain in the central and northern areas. The south and southwest regions are mainly distributed in the southeast hills, including Yandang Mountain, Huangshan Mountain, Dabie Mountain, and other famous mountain tourist attractions. The central part is mainly the Yangtze River and the Yangtze River Delta. To the north of the Yangtze River are the Jianghuai Plain and the Huanghuai Plain, including the middle reaches of the Huaihe River Plain. Topographic conditions determine that the distribution of natural ecological tourist attractions is mostly concentrated in the southern part of the Yangtze River Delta, while the western part is flat. Due to historical reasons, there are many poor areas and tourism development is late, so the agglomeration area of natural ecological tourist attractions has not yet been formed. Since ancient times, the mountainous area has been a battle place for military strategists. Its special topographic conditions determine its important military strategic location, so the southern part of the Yangtze River Delta has become a gathering area of historical and cultural tourist attractions.

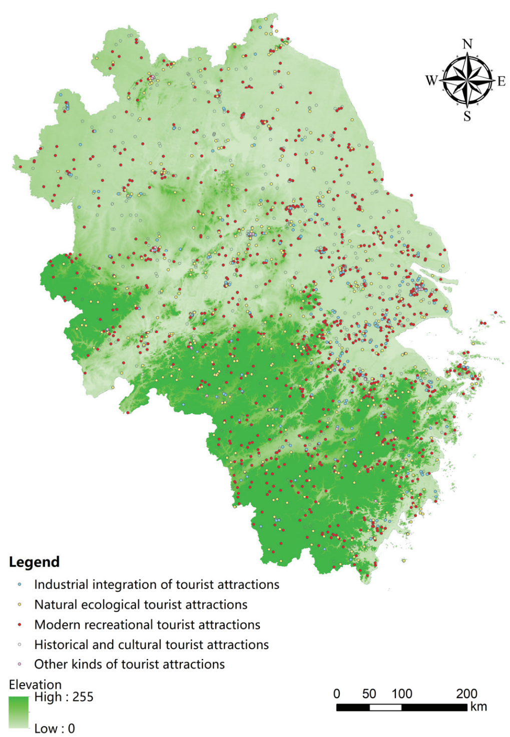

Figure 5. Coupling of topography and the spatial distribution of tourist attractions.

Because of the flat terrain, pleasant climate, and developed water system, the Yangtze River Delta has many kinds of natural ecological tourist attractions, including mountain type natural ecological tourist attractions represented by Jiuhua Mountain, river and lake type natural ecological tourist attractions represented by Taihu Lake and Yangtze River, and island type natural ecological tourist attractions represented by Zhoushan Islands and Chongming Island. In addition, flat terrain is the base of human activities, thus forming human history and culture, leaving a wealth of material and intangible cultural heritage. For example, the Beijing-Hangzhou Grand Canal built in ancient China made Nanjing, Suzhou, Hangzhou, and Xuzhou become important commercial centers and military strongholds, enriching historical and cultural tourism resources in the Yangtze River Delta. In summary, cultural tourist attractions, such as historical tourist attractions, modern recreation tourist attractions, and industrial integration tourist attractions, are more distributed in the plain areas or areas with lower elevations, while natural tourist attractions of famous mountains are more distributed in areas with higher elevations. Areas with flat terrain and low altitude are suitable for production and living activities and are rich in tourism resources. Therefore, altitude determines the type and distribution of tourist attractions to a certain extent.

4.1.2. Influence Analysis of the River System

The Yangtze River Delta area has a developed water system and numerous rivers. Coastal areas are the main places of human activities and the birthplace of civilization, which affect the formation of cultural tourism resources. The river system itself is at the same time a natural tourism resource and is important for the construction of landscape elements, with waterfalls, fall deep pools, great tides, flowing water, spring discharge pools, and mountain streams giving the landscape visual esthetics and beauty [58–61]. The Yangtze River Delta area river network density is high, vertical, and horizontal. From the perspective of water system characteristics, most areas of the Yangtze River Delta belong to the Yangtze River basin, and the water system has a close coupling relationship with the water landscape tourist attractions; that is, the tourist attractions formed by relying on the water landscape tourism resources form a banded distribution along the river valley. In this study, using the Arcmap software buffer analysis tool, the river system was analyzed with a 3-km buffer zone from the main water system (Figure 6). We found that 292 tourist attractions fall within the 3-km buffer zone, accounting for 13.5% of the total number of tourist attractions. This shows that the river system is an important factor affecting the spatial distribution of tourist attractions.

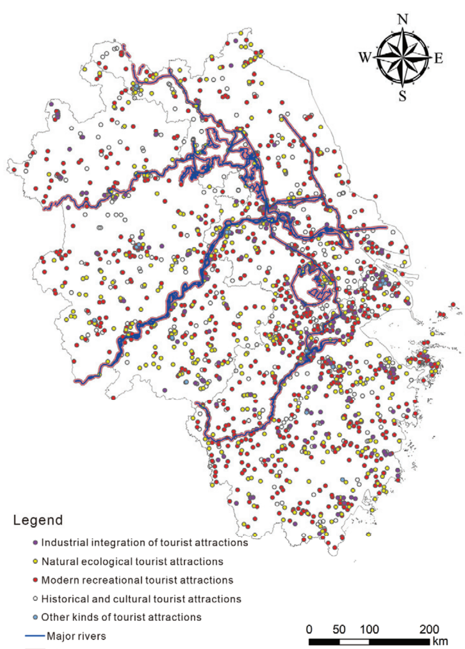

Figure 6. Coupling of the river system and the spatial distribution of tourist attractions.

4.2. Traffic Factors

Location and transportation factors determine the accessibility of tourist attractions [43]. Large numbers of tourists entering tourist attractions will necessitate transmission facilities to improve and upgrade tourist services and promote the quality of tourist attractions; at the same time, traffic lines linking with feeders can provide a "corridor effect" to promote the surrounding traffic service level of ascension, dilute the boundary of the block effect of regional tourism development, speed up the process of spatial agglomeration tourist attractions, and promote tourist attractions by the isolated dotted steering axis or mesh layout.

Transportation in the Yangtze River Delta is developed. In 2020, the total number of passengers transported in 41 cities of the Yangtze River Delta was 190.286 million, among which, the number of railway passengers accounted for 69%, highway passengers 26%, and ports and airports 4%, all ranking among the top in China. In particular, 41 cities in the Yangtze River Delta, except Zhoushan, have opened high-speed railway lines, and there are a total of 174 high-speed railway stations. Shanghai, Jiangsu, Zhejiang, and Anhui provinces and one city have a total length of 5984.8 km. Among them, Shanghai has 172.3 km of high-speed railway, Jiangsu 2021 km, Zhejiang 1510.1 km, and Anhui 2281.4 km.

Efficient modern transportation has shortened the time distance between cities, allowing local markets to spill over. For example, the 1-h traffic line between Shanghai, Nanjing, and Hangzhou has given rise to a series of four tourist attractions, especially promoting the obvious gathering trend of modern recreational tourist attractions that rely more on traffic and markets.

In this study, Arcmap 10.7 software, a GIS software developed by the Environmental Systems Research Institute (ESRI) in Redlands, California, USA, was used to construct a 10-km buffer zone of main traffic arteries (mainly including railways and main highways) (Figure 7). It was further concluded that a total of 1375 tourist attractions were distributed within the 10-km buffer zone of main traffic lines, accounting for 63.83% of the total number of tourist attractions. Among them, there are 1051 tourist attractions along the main highway routes, accounting for 48.79% of the total number of tourist attractions. The number of tourist attractions along the railway line is 1072, accounting for 49.77% of the total number of tourist attractions.

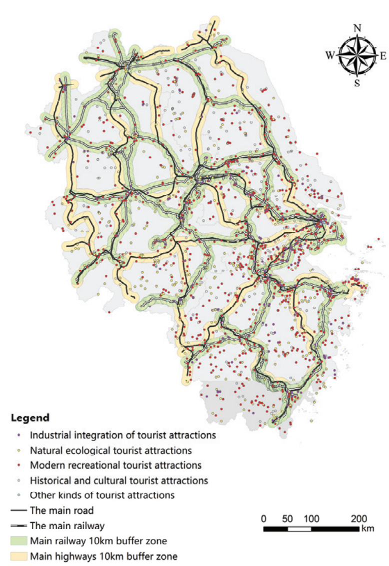

Figure 7. Coupling of the main traffic lines and the spatial distribution of tourist attractions.

Generally, the density of tourist attractions is consistent with the density of the traffic network, showing characteristics of being higher in the east than in the west, and higher in the south than in the north. Traffic factors affect the accessibility of tourist attractions and change tourists' mode of travel. At present, southern Jiangsu, Shanghai, and northern Zhejiang have entered the development stage of city integration, which has obvious transportation advantages compared with northern Jiangsu and northern Anhui.

4.3. Social and Economic Factors

Social and economic factors promote the development of tourist attractions. Similarly, the improvement of the social and economic level also provides an economic basis for the development of tourism. With the improvement of residents' income levels, their tourism demand is gradually increasing. According to the per capita GDP of cities and the distribution of tourist attractions in 2020, Shanghai has 130, and its per capita GDP is 155,800 yuan, both of which are far ahead of other cities. Both measures are also high in Suzhou, Hangzhou, Nanjing, and Ningbo but low in Yicheng, Huaibei, and Tongling. There is a strong correlation between the level of social and economic development and the number of tourist attractions (Figure 8). Social and economic factors can affect the development of tourist attractions in different regions. In 2020, the tourism industry was seriously affected by the COVID-19 epidemic, but the free admission policy of A-level tourist attractions in the Yangtze River Delta played an important role in stimulating the rapid recovery of the tourism industry and stimulating tourist consumption. The rise and prosperity of the tourism industry fundamentally stimulates the development of tourist attractions. The formation and development of the five tourist attractions are directly affected by the economic level.

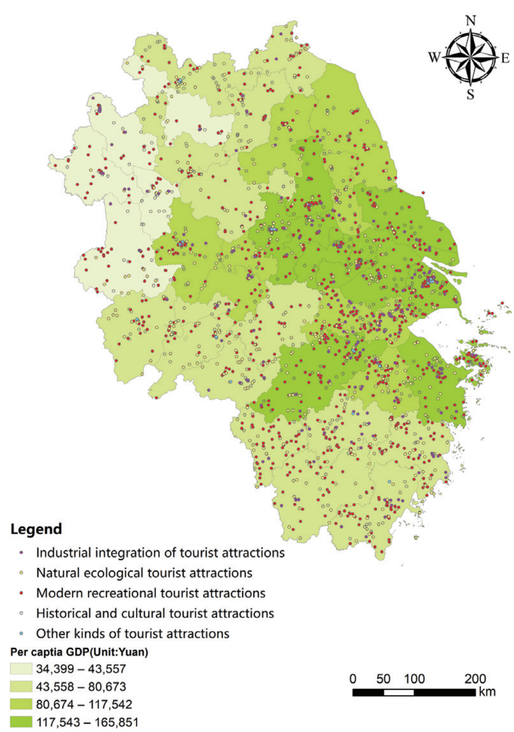

Figure 8. The coupling between social economy and the distribution of tourist attractions.

5. Discussion

Although it is very important to study the types of tourist attractions and the degree of spatial agglomeration of tourist attractions, there is limited research on the spatial patterns and influencing factors of overall tourist attractions in specific regions and their components. To address the research gap and further study the spatial structure of the distribution of different types of tourist attractions, this study not only classifies the tourist attractions in the Yangtze River Delta but also explores their spatial structure characteristics and influencing factors.

Tourist attractions are widely distributed in terms of spatial density and spatial distribution characteristics. This may be due to the rich tourism resources and developed regional economy, which ultimately has created a large number of tourist attractions and a high degree of development. This finding validates the view of Wang et al. [28]. In addition, both the overall spatial distribution of tourist attractions and the spatial distribution of their various types show a significant agglomeration and trend from northwest to southeast. Among them, the natural ecological tourist attractions in Huangshan city and Nanjing city are the core. The historical and cultural tourist attractions are centered in Shanghai, Hangzhou, and Nanjing. Shanghai is the core of modern recreational tourist attractions, and the core of industrial integration tourist attractions are in Shanghai, Nanjing, and Hangzhou. Other types of tourist attractions are mainly concentrated in Shanghai, Hangzhou, Nanjing, Hefei, and Huangshan. It is easy to observe that the core clustering places of tourist attractions are distributed in municipalities directly under the central government (Shanghai), provincial capital cities (Hangzhou, Nanjing, and Hefei), or tourist cities (Huangshan and Ningbo), and the number of tourist attractions decreases from these cities (as the core) to surrounding areas. The basic reasons for this discovery may be that the regional central city or city is a famous tourist resort, with strong regional economic development and good infrastructure, making it a destination of choice for tourists; however, the limited bearing capacity of a single tourist attraction may deter tourists and be the driver for more tourist attractions to develop more fully. Thus, the viewpoints of Gunn et al. are supported and conform to the law of distance attenuation [62,63].

The spatial patterns of tourist attractions are mainly affected by three factors: physical geography, social economy, and traffic. The first choice for site selection of tourist attractions in the Yangtze River Delta is along rivers, traffic routes, or areas with concentrated tourism resources and a developed economy. This also validates the findings of Truchet et al. [55].

This study contributes the following to the broad literature. Previous studies mainly focused on the classification, evaluation, and spatial distribution of tourism resources, ignoring the central role of tourist attractions. Therefore, the empirical analysis of the spatial patterns of different types of tourist attractions in this study can supplement relevant research on tourist destinations to a certain extent. In addition, this study reveals that physical geography, transportation accessibility, and social and economic conditions have a significant impact on the development and layout of tourist attractions.

This study also provides a basis for identifying advantageous tourism resources and determining the growth poles of tourist attractions. It provides a reference for the rational development of tourism resources, the orientation of tourism development, and corresponding tourism marketing strategies. In addition, the overall comprehensive analysis and classification of the spatial distribution characteristics of tourist attractions in the Yangtze River Delta are conducive to overcoming the defects of traditional official data, clarifying the types of tourism resources in surrounding cities, mining the characteristic resources of surrounding cities, and providing a reference for tourism positioning, adapting measures to local conditions, and developing characteristics and personalized tourism modes to promote the sustainable development of tourism in the Yangtze River Delta region.

6. Conclusions

In this study, 2166 tourist attractions in the Yangtze River Delta region were selected as the research object. Using ArcMap 10.7 software, a GIS software developed by the

Environmental Systems Research Institute (ESRI) in Redlands, CA, USA, the spatial patterns of tourist attractions were analyzed using the methods of nearest proximity index, kernel density analysis, standard deviation ellipse, and hot spot analysis. Spatial superposition analysis was used to clarify the relationship between the spatial patterns of tourist attractions and physical geography, transportation, and social and economic factors.

The main conclusions of this study are as follows.

First, among the 2166 tourist attractions, the number and proportion of the category of modern recreational tourist attractions are the highest. Natural ecological tourist attractions and historical and cultural tourist attractions also have a large proportion. The proportion of industrial integration tourist attractions and other kinds of tourist attractions is relatively small. In general, the spatial patterns of these tourist attractions are more in the north than the south, and more in the east than the west. The spatial density of tourist attractions in Shanghai is much higher than that of other regions, followed by Jiangsu and Zhejiang, while Anhui has the lowest spatial density. Such a conclusion is consistent with the research conclusions of Xu et al. [64] and Han et al. [65]. Xu et al. and Han et al. also pointed out in their studies that the density of high-grade tourist attractions in the eastern part of the Yangtze River Delta was higher than that in the western part, which was consistent with the conclusion of this study. Furthermore, they showed that the density of high-grade tourist attractions in the Yangtze River Delta was higher in the south than in the north. This is because there are more low-grade tourist attractions in the northern part of the Yangtze River Delta than in the southern part. If all tourist attractions are regarded as research objects, there will be a spatial pattern with more tourist attractions in the north and fewer in the south.

Second, the five types of tourist attractions show significant spatial aggregation, including natural ecological tourist attractions in Nanjing, Huangshan area; the historical and cultural tourist attractions cluster in the vicinity of Shanghai, Hangzhou, and Nanjing, forming a T-shaped cluster state; and modern recreational tourist attractions cluster in Shanghai and Hangzhou. Industrial integration tourist attractions are clustered in Shanghai, Nanjing, and Hangzhou and other kinds of tourist attractions are prominent in Shanghai; there is no obvious agglomeration in the region. Due to the different classifications of tourist attractions, the conclusions cannot be compared with those of other scholars. However, from only the agglomeration area of tourist attractions, many scholars also believe that Shanghai, Nanjing, Hangzhou, Ningbo, and Huangshan are the cities with the most agglomeration of tourist attractions [11,64,65].

Third, the spatial distribution direction of modern recreational tourist attractions and industrial integration of tourist attractions is obvious. The centripetal force of the spatial distribution of industrial integration of tourist attractions and historical and cultural tourist attractions is stronger. The deviation angles of the standard deviation ellipses of the five types of tourist attractions are all between 90 and 180 degrees, showing a northwest-southeast trend. This is consistent with the shape trend of the Yangtze River Delta administrative region.

Fourth, there are different degrees of cold spots and hot spots in the spatial patterns of the five types of tourist attractions. Except for natural ecological tourist attractions in Nanjing and Huangshan, the other four types of tourist attractions are located in Shanghai and its adjacent areas. This conclusion validates the study of Xu et al. who, based on the panel data of 3A or above tourist attractions in the Yangtze River Delta from 2001 to 2015, comprehensively applied mathematical statistics and GIS spatial analysis methods, and concluded that Shanghai has always been the polar core center of the Yangtze River Delta region [64].

Fifth, physical geography, transportation, and social and economic factors affect the spatial patterns of tourist attractions. This is partly consistent with the research conclusion of Kang et al. [16] and Wu et al. [17]. They believe that the spatial pattern of tourist attractions is affected by four factors: resource endowment, transportation network, natural environment, and economic level. The conclusion is compared with the lack of resource endowment factor. However, this study classifies tourist attractions based on tourism resources, so resource endowment will naturally have an impact on the spatial pattern of tourist attractions. In short, this study comprehensively analyzed the spatial distribution characteristics and differences of different types of tourist attractions in the Yangtze River Delta region. The advantages of this approach are that it can overcome the defects of traditional official data and clarify the types of tourism resources in various cities, so as to provide a reference for each city to excavate characteristic resources, find accurate tourism positioning, and develop characteristic and personalized tourism models according to local conditions so as to promote the sustainable development of tourism in the Yangtze River Delta region. The conclusions obtained in this study effectively make up for the lack of research by Yang et al. [66] and Yao et al. [67].

However, this study has the following limitations. It did not assign weight to the level of tourist attractions in the data calculation and analysis. In addition, the analysis of the influencing factors of the spatial patterns of tourist attractions lacked combined qualitative and quantitative methods, resulting in a lack of in-depth analysis of the influencing factors. In future research, the comprehensive use of mathematical statistics could be used for further exploration of the data.

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The Spatial-Temporal Evolution of Population in the Yangtze River Delta, China: An Urban Hierarchy Perspective

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Abstract: The reason for changes in ranking within urban systems is the subject of much debate. Employing the census data from 1990 to 2020, this paper investigates population dynamics across urban hierarchies and its influencing factors in the Yangtze River Delta. The results reveal an upward pattern of population dynamics and show that the advantages of high-ranking cities in population gathering are obvious, though they have declined recently. Based on a framework of urban amenity and the ridge regression model, the authors argue that concerns of residents in choosing cities in which to settle are gradually changing from economic opportunities to multidimensional amenities, finding that the influencing mechanisms vary across time. This is slightly different from Glaeser's consumer cities; economic gains, as physiological needs, are always important for population growth. As higher-level needs, social and natural amenities, including Internet accessibility and urban green space, did not affect growth until the turn of the new millennium. In terms of negative factors, the 'crowding-out effect' of living costs and environmental pollution are not significant, as theoretically expected, suggesting that residents tend to care more about development opportunities than the negative impacts of living in high-ranking cities. Finally, policies are proposed to promote population growth and the coordinated development of large, medium, and small cities in the Yangtze River Delta.

Keywords: population distribution; spatiotemporal dynamics; urban hierarchy; urban amenity; Yangtze River Delta

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1. Introduction

As a marker of the economic health and vitality of cities and of places, population dynamics is a pressing issue of great concern to both academics and policy makers [1,2]. Particularly in an era with an aging population and a low fertility rate, the changes in population have a more prominent effect on the variation in city size than ever before [3]. Understanding the distribution of population and its growth across hierarchies takes on great importance for forecasting the evolution of the urban system and determining socioeconomic trends [4–6]. To date, two strands in the literature have been identified to uncover the pattern of population dynamics among cities: the upward pattern and the downward pattern. In the former strand, scholars found that populations moved from rural areas to nearby towns and then up the urban hierarchy to (larger) cities [7,8]. People tend to self-select upward mobility driven by rapid economic growth and higher prospects [9]. Higher-ranking cities are more likely to attract investments and firms from home and abroad, creating a large immigrant population [10]. For example, of the total population in the metro areas, more than 60% is concentrated in the 10 largest areas in Japan [11]. Approximately 21% of residents are concentrated in megacities in China [7,12]. In addition, others have argued that the generosity of the local welfare system may attract more population gathering in large cities [13]. For instance, scholars found that the population is more likely to be clustered in states with generous welfare systems in the United States [14,15]. In Europe, people gather in higher-ranking cities in search of welfare magnet effects [13]. In Germany, people tend to cluster in welfare states with equal opportunities and reduced income differences [16]. In summary, population dynamics in many countries tend to follow an upward pattern along the urban hierarchy.

Regarding the second strand, some studies identified a downward and decentralized tendency in developed countries or areas [6,17]. For instance, scholars found that most counties gained people from the nation's most populous cities in the United States [1,17,18]. That is, many of the major movements in the system of internal (or domestic) migration are flows down the urban hierarchy from central cities to adjacent suburbs which, in turn, sent migrants to exurban areas [18]. Similarly, a strengthening downward trend in the current migration pattern has also been identified in China in the 2020s [6]. With the outward transfer of industries and highly interlinked transportation, some people may move away from megacities to lower-ranking cities in search of better living conditions [6,19]. Micropolitan cities often occupy key positions at the interface of migration up and down the national urban hierarchy, such as the United Kingdom, Norway, and the United States [20,21].

Previous studies have found that the distribution of population in differently ranked cities is consistent with the process of urbanization. In the early stages of urbanization, the population gathers in small towns, which is mainly due to the development of factories and industries in these areas that attract a large number of rural surplus labor. In general, this happens in both developing countries and regions. For example, in 2012, 45% of the Asian population was concentrated in small cities under 500,000 [22], and 57% of the African population of Africa was clustered in small cities [23]. During the accelerated development period of urbanization, the population concentrated in medium and large cities due to economies of agglomeration [24,25]. Large cities can attract more domestic and foreign enterprises and investments, which provide more employment opportunities and higher wages, and thus promote further population agglomeration in large cities [10,26]. The research has also shown that social welfare increasingly has a role in people's residential choices [27,28]. However, when the ratio of population to urban agglomerates reaches a certain level, the dispersing effect created by rising costs and environmental pollution in large cities forces people with low skills or people seeking a high quality of life out to lower-ranking cities, which gives rise to a trend known as counter-urbanization [29]. Throughout much of the developed world, a new scenario of population movement is following the migratory steps of moving from large cities to nearby smaller cities, such as in the USA and Sweden [17,30]. In the period of re-urbanization, central locations of many cities have been transformed into areas that may be appealing to the population. These include not only the physical aspects of central districts, such as urban amenities and walkable streets, but also the cultural and social dimensions, such as a dynamic and diverse atmosphere [31,32]. This is exemplified in the work undertaken by Florida et al. and Glaeser et al. Cities with more restaurants and live performance theaters per capita have grown more quickly over the past 40 years in both the USA and France [33,34].

In general, studies have paid more attention to cities in developed countries, such as those in America and Europe. Few studies focused on urban cases in developing countries, such as China. The evolution of regional population distribution and the influencing factors calls for comparative research [35]. With respect to the case in transitional China, higher-ranking cities are more likely to attract investment from the central government and from abroad, due to the reform of decentralization since the early 1990s [36]. As a consequence, higher-ranking cities tend to have advantages in both economic opportunities and public service, and thereby cluster larger parts of the population. However, the state has, on several occasions, formulated a policy of controlling the size of large cities in a bid to alleviate the development pressure of large/megacities and balance the development of cities at different levels [7]. For instance, the maximum population in Beijing and Shanghai has been strictly limited by the urban master plans of the two megacities in 2016 and 2017, respectively. The academic community has not yet reached a consensus regarding the trend of population agglomerating dynamics.

The Yangtze River Delta was selected as a case study in this research for two reasons. First, the urban system in the YRD, on the one hand, is a typical example within the context of marketization and urbanization in China and, on the other, is representative of the changes in the world's urban system. Second, the YRD, as one of the six megalopolises in the world, is widely recognized as a polycentric region, making it an ideal case study of the attractiveness to people of different ranks of cities.

To better demonstrate the urbanization path in China, this article portrays the pattern of population dynamics across urban hierarchies in the Yangtze River Delta (YRD) with the help of the population census data from 1990, 2000, 2010, and 2020. More specifically, two research questions are addressed: (1) What are the changes in population distribution across urban hierarchies? (2) What matters for the growth of cities in hierarchical terms? In the following sections, we first provide a brief review of the study area, followed by a discussion of the data and methodology. We then begin to examine the population dynamics patterns and uneven distribution in the YRD. Thereafter, the determinants of the mentioned patterns are discussed. Finally, we conclude with major findings and policy implications.

2. Methodology and Materials

2.1. Study Area and Data Collection

Located on the eastern coast of China, the YRD is one of the most urbanized regions in the country and has attracted a considerable number of migrants from outside the region. As Figure 1 shows, the study area includes Shanghai and three neighboring provinces (i.e., Jiangsu, Zhejiang, and Anhui), covering approximately 358,000 square kilometers with a total population of 235 million in 2020. The area is home to 15 percent of China's population and contributes roughly a quarter of the country's GDP. With a well-developed urban system, the YRD is an ideal area to investigate population dynamics and the growth of cities. Based on geographical locations and development levels, the authors further divide the YRD region into 9 sub-regions: Shanghai, Southern Jiangsu, Central Jiangsu, Northern Jiangsu, Northern Zhejiang, Southern Zhejiang, Southern Anhui, Northern Anhui, and Central Anhui.

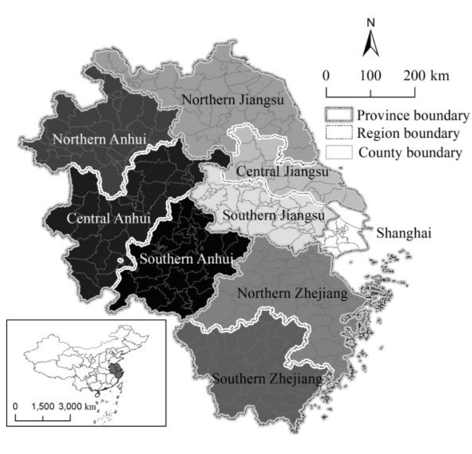

Figure 1. Location and organization of the YRD.

Population size has long been employed as an indicator to identify hierarchical levels of cities. According to the standard issued by the State Council in 2010, we classified cities into seven levels based on data from four censuses in 1990, 2000, 2010, and 2020, that is, mega metropolis (with at least 10 million dwellers), major metropolis (ranging from 5 to 10 million residents), large cities (from 1 to 5 million inhabitants, including type I and type II with 3 million as the threshold), medium cities (from 500,000 to 1 million dwellers), and small cities (less than 500,000 residents, including type I and type II with 200,000 as the threshold). To further explore the determinants of population dynamics, we also collected data on influencing factors from various statistical yearbooks based on the theoretical framework in the following section. Details of the data source are listed in Table 1.

Table 1. List of variables.

Type	Variables	Description	Data Sources
Economic amenity	GDP	Gross domestic product (CNY 100 million)	China City Statistical Yearbook and China County Statistical Yearbook
	employ	Number of employees (persons)	Shanghai, Jiangsu, Anhui and Zhejiang Statistical Yearbook 1991–2021
	livexp	Consumption expenditure of residents (CNY)	City and District Statistical Yearbook 1991–2021
	hp	Average house price (CNY)	Python from anjuke.com
Social amenity	*bed*	Number of beds in hospitals (unit)	China City Statistical Yearbook and China County Statistical Yearbook
	edu	Education expenditure(CNY 10,000)	Shanghai, Jiangsu, Anhui and Zhejiang Statistical Yearbook 1991–2021
	FDI	Foreign direct investment (USD 100 million)	China City Statistical Yearbook and China County Statistical Yearbook
	inter	Number of Internet users (household)	Shanghai, Jiangsu, Anhui and Zhejiang Statistical Yearbook 1991–2021
Natural amenity	*pm*2.5	Mean annual value of PM2.5 ($\mu g/m^3$)	Estimated by Macrodata.com
	green	Public green space (hectare)	Shanghai, Jiangsu, Anhui and Zhejiang Statistical Yearbook 1991–2021

2.2. Theoretical Framework

To shed further light on the driving impetus of population dynamics, we propose a conceptual framework in Figure 2 that is based on the theory of urban amenity [37,38]. We define urban amenities as location-specific marketed and nonmarketed attributes, such as income expectation, living costs, facilities and public services, environmental quality, and social atmosphere, which make people's living and working in a particular city more convenient. In general, residents tend to settle in cities based on an evaluation of both economic and other non-marketing amenities (including the natural and the social) [39]. It is widely recognized that big cities offer more job opportunities, higher income, better public services, and a welcoming social atmosphere with higher living costs and house prices, while small cities have a beautiful environment and lower living costs [40]. In other words, people choose to settle in cities of different ranks in order to meet their heterogeneous needs. Economically, people's primary need is to generate enough income to cover housing and living costs. According to Maslow's hierarchy of needs, when basic needs have been met, higher-level needs should be the focus, such as access to public services, an open-minded or a welcoming social atmosphere, and a better environment. These needs are related to social and natural amenities.

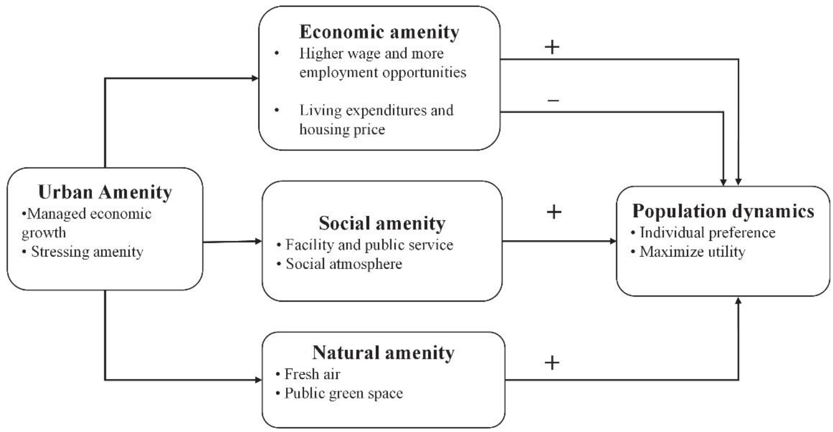

Figure 2. Framework of population dynamics across urban hierarchy.

First, availability of economic amenities has been widely viewed as a principal determinant of individual residential choice [30]. Residents gather in cities with a tradeoff between personal benefits and costs. On the one hand, high-ranking cities are more attractive to people due to better income expectations and job opportunities, because large cities can enjoy the external economy, such as economies of scale, saving transaction costs, and knowledge spillover [41]. On the other hand, the effects of income growth would be weakened by the 'crowding-out effect' caused by a rising cost of living and house prices due to population agglomeration in large cities [28]. Thus, economic development and income level are positive indices, but living costs and house prices are negative indices.

Second, public services and social atmosphere—as the key to social amenities—arguably fulfill higher-level needs for residents once basic needs have been satisfied. According to the notion of voting with one's feet, public services are closely associated with residents' well-being and thus affect the distribution of the population across cities [2,42]. In advanced regions, cities become new areas of population growth by increasing the provision of high-quality facilities and public services [43]. In their developing counterparts, population growth tends to slow down due to congestion of public services and lack of infrastructure [44]. In addition, social atmosphere, referring to a climate of openness, forbearance, and possibility, would profoundly influence population gathering in cities as well. Residents are more likely to cluster in large cities with higher openness to the global market and information, as it is useful to decrease inequalities and increase social trust by providing more opportunities and possibilities [45]. In particular, within the context of globalization, openness to the world matters more for population agglomeration. Accessibility to information is also an important consideration for perceptions of social atmosphere. Information and communications technology (ICT) can, on the one hand, facilitate individuals' participation in economic activities [46], and on the other hand, help in reducing decision errors caused by incomplete information. For instance, both online learning and working from home during the COVID-19 pandemic depend on the Internet and ICT. Stemming from these, we propose the hypothesis that openness to the global market and the level of informatization of specific cities have a positive impact on population growth.

Third, natural amenities are widely considered as a positive driver of population gathering, due to their positive impact on human well-being, physical and mental alike [47]. Scholars have shown that urban green space plays an important role in attracting people in terms of its ecological, recreational, cultural, and educational function, which helps to reduce working pressure, eliminate negative mood, and promote psychological health [48]. By contrast, air pollution impedes population growth in big cities [49], which is conceptualized as the 'crowding-out effect'. The hypothesis is that green space has a positive impact on population in high-ranking cities but air pollution has a negative impact. On this basis, we constructed an indices system of urban amenities to examine the driving mechanism of population dynamics. As Table 1 shows, the gross domestic product (GDP) and number of employees (*employ*) indicate revenue prospects and employment opportunities, respectively. Per capita consumption expenditure of residents (*livexp*) and average house price (*hp*) show the impact of living costs. The annual value of PM2.5 (*pm*2.5) and area of green space (*green*) were employed to test environmental quality. With regard to public services, the number of hospital beds (*bed*) and expenditure on education (*edu*) were selected. Foreign direct invest (FDI) and Internet accessibility (*inter*) indicate the openness of the social atmosphere. In addition, we introduced urban hierarchy (*rank*) as a control variable.

2.3. Methodology

The authors utilized multiple regression models to empirically test the relationship between total population across urban hierarchy and urban amenity. In these models, the dependent variable is total population. The main explanatory variables of interest are economic amenities (i.e., GDP, employment, living expenditure, and house price), social amenities (i.e., number of beds in hospitals, education expenditure, FDI, and number of Internet users), and natural amenities (i.e., PM2.5 and public green space). The control variable is the rank of cities.

To shed further light on the detailed determinants of population dynamics, the authors employed OLS regression models to test the aforementioned hypothesis. First, we conducted collinearity analysis using the OLS model for three periods. The VIF of GDP and beds were greater than 10 and the tolerance was less than 0. Thus, we used the ridge regression model to overcome the presence of collinearity by adding a degree of bias to the regression estimation. To ensure comparability of the three periods, we chose k = 0.18 after viewing the ridge trace.

3. Results and Analysis

3.1. Patterns of Population Dynamics

3.1.1. Temporal Evolution of Population across Hierarchies

As Figure 3 shows, the YRD has faced a strong tendency toward population agglomeration, namely population gathering within urban areas, such as high-ranking cities. In 1990, approximately 66% of the population dwelled in rural counties, with only 34% in cities at various levels. By 2020, the size of the population in rural counties decreased by 26%, becoming much smaller than urban counterparts, which increased by 74%, a situation that well echoes the unprecedented urbanization in transitional China. Compared with other ranking cities, megacities and major metropolises have witnessed the largest population growth of 5.2 million in the past three decades. Specifically, the pattern of population growth across hierarchies is reported as follows:

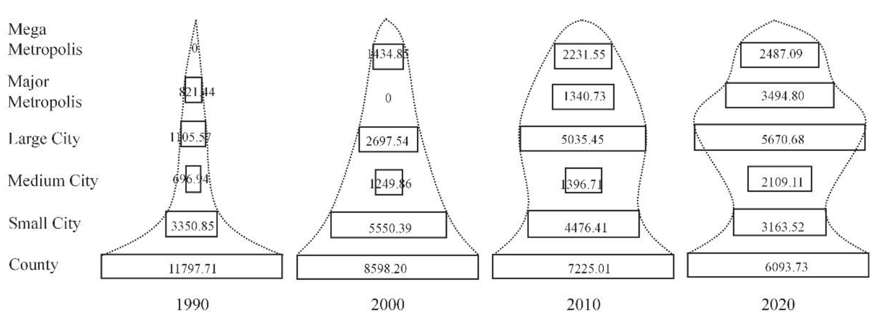

Figure 3. Total population across hierarchies from 1990 to 2020 (unit: 10,000).

1990–2000: Rise in medium and small cities. With the upward migration of population, a total of 17 small cities achieved a rank jump in the last decade of the 20th century, including 5 growing into type II large cities and 12 into medium-sized cities (Figure 4). Meanwhile, 37 rural counties developed into small cities. Consequently, medium and small cities witnessed the largest population growth, accounting for 58% of the total growth in the YRD. By contrast, only 15% of the growth occurred in large cities. Shanghai, as the only major metropolis, developed into a mega metropolis with a total growth of 6.13 million. Notably, Yancheng experienced a population decline of approximately 50% due to the separation of Yandu County from its suburb, downgrading it from a large to a medium-sized city in 2010. Regarding potential reasons for the rise of small and medium-sized cities during this stage, scholars argue for the decentralization of administrative and fiscal authority in transitional China as well as household registration (hukou) control in large cities [6].

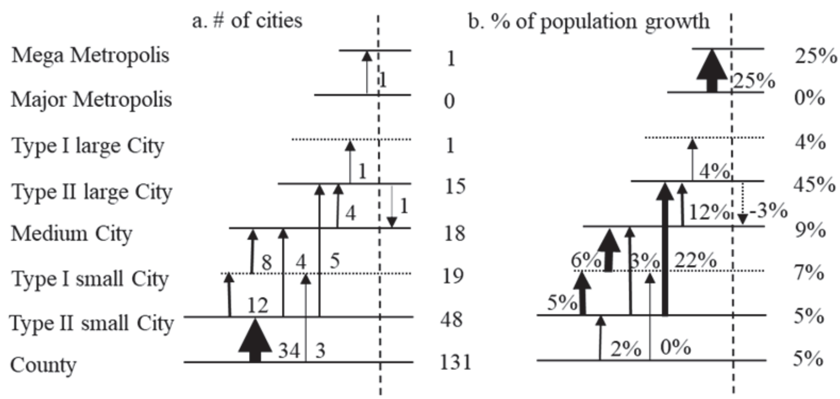

Figure 4. Number of cities and share of cities' increment to total population growth across hierarchies in 1990–2000. Note: a indicates number of different ranking cities, b indicates the share of cities' population growth. Numbers or proportions near the arrow present changes in the time periods. Numbers on the right of lines are values of the base period. The same applies to the figures below.

2000–2010: Booming of large cities and emerging megacities. With the loosening of migration policy and hukou control, large cities witnessed the largest growth in the first decade of the new century. Specifically, more than half (54%) of the population growth in the YRD was concentrated in large cities of which the share of type I and type II large cities accounted for 19% and 35%, respectively (Figure 5). The upgrading of small and medium cities to large was also pronounced. Three small cities and eight medium-sized cities grew into large cities. Another notable change is the upgrading of Nanjing and Hangzhou from large cities to major metropolises, which, coupled with the fact that Shanghai's population had skyrocketed by 7.96 million, suggests the popularity of megacities in this decade. In addition to the jump in city ranks, population growth within each rank (particularly small cities) was also worth noting. A total of 19 small cities grew from type I to type II, with their average size of population surpassing 400,000.

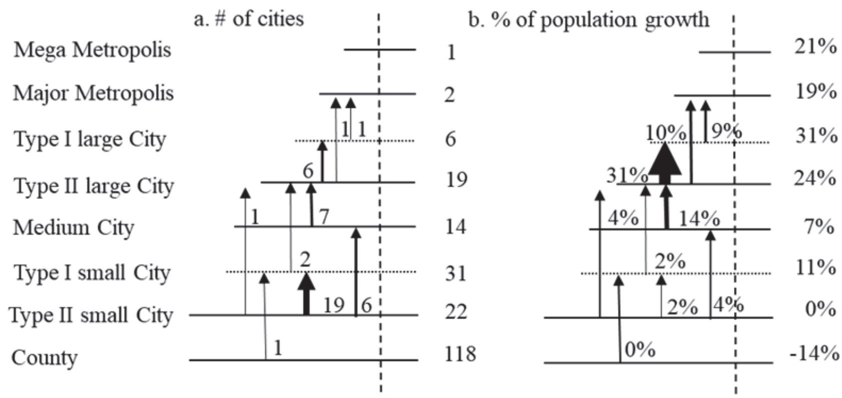

Figure 5. Number of cities and share of cities' increment to total population growth across hierarchies in 2000–2010.

2010–2020: Popularity of large cities and slowdowns in megacities. In the last 10 years, 82% of the population growth was witnessed in large cities, with only 18% in their small and medium-sized counterparts (Figure 6). By the end of 2020, the number of large cities (both type I and II) in the YRD reached 27, accounting for 54% of the total number of cities. Compared with the previous decade, the annual rate of population growth in megacities decreased by 50% (from 10% to 5%), although three large cities (i.e., Suzhou, Hefei, and Ningbo) became new major cities. This may partially indicate the declining attractiveness of megacities to populations within the context of abrupt increases in living pressures. On the other hand, mobility toward large cities in the YRD is still the mainstream of population dynamics in this decade, though return migration from the coast has been appearing in inland China. Similar to the case of Yancheng in 2000–2010, Chaohu was downgraded from a medium-sized to a small city owing to administrative adjustment.

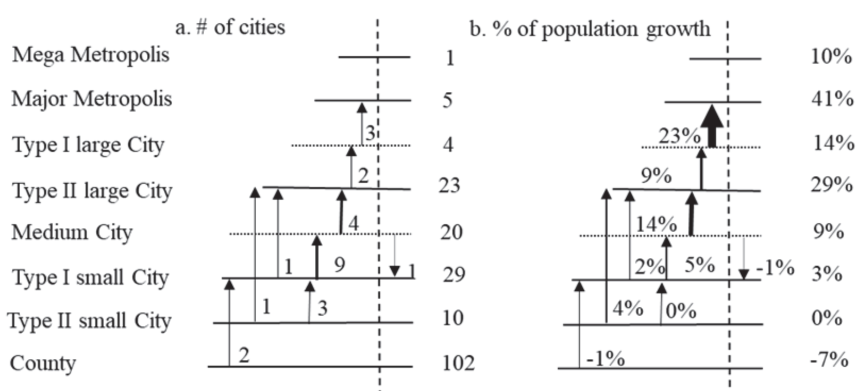

Figure 6. Number of cities and share of cities' increment to total population growth across hierarchies in 2010–2020.

3.1.2. Spatial Evolution of Population

To shed further light on the patterns of population dynamics in the YRD, we charted the geographical distribution of population growth over the past three decades (Figure 7). Here, we highlight three arguments. First, a gradient growth pattern from peripheries to centers is demonstrated. In the first decade, growth was relatively scattered and evenly located in the YRD with only a few dark-colored growth centers. The advantages of large cities in terms of population agglomeration were not obvious, which was to some extent consistent with the aforementioned findings on the rise of medium and small cities in the 1990s. Entering the new century, counties/cities in the vast peripheries faced a rapid population decline with the growth of cities in southern Jiangsu Province and coastal Zhejiang Province, most of which were classified as large cities. In the last decade, areas of population increase and decrease were almost reversed compared to the 1990s. In summary, population movement can be considered as an upward agglomeration from rural counties to geographically close small and medium-sized cities and then to large cities and megacities in the southeast.

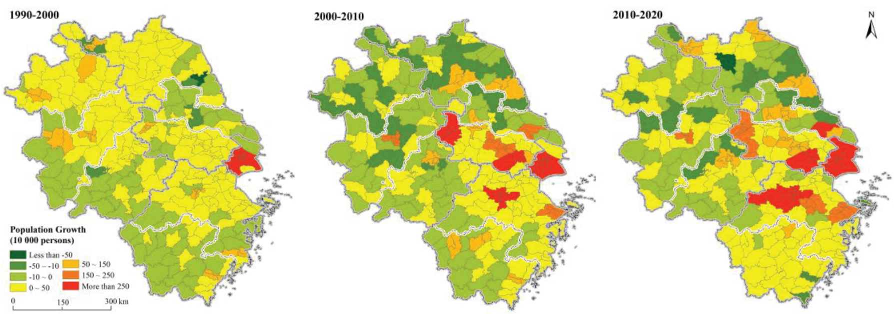

Figure 7. Changes in population spatial distribution from 1990 to 2020.

Second, areas with population growth shrunk first and thereafter expanded, indicating a possible pattern of reversion in the YRD. That is, the population in large cities reaches a certain threshold after experiencing rapid growth and thereafter may leave opportunities for further development of the surrounding cities. This may be partly due to the spillovers and 'crowding-out effects' of megacities [50,51] but may also be because of the voluntary exurbanization of dwellers in megacities [52] or the sub-optimal selection of low-skilled immigrants who cannot afford the cost of living in megacities [53,54]. This suggests that the tide of population agglomeration to mega if not large cities may turn in the future.

Third, trends and the driving impetus of population dynamics may vary across regions/stages, though upward mobility tends to be the mainstream in the YRD and beyond. In the early stage (1990s), agglomeration to local or nearby cities was the mainstream of population dynamics; in the advanced stage (2010s), there might be a similar situation but for different reasons. For the former (e.g., the case of northern Anhui and Jiangsu in the 1990s), the ability of migrants matters; for the latter (e.g., the case of southern Zhejiang in the 2010s), migrating needs determine population growth. Only in the rapidly urbanizing era of the 2000s can long-distance movement from the peripheries to the core be witnessed.

3.2. *Influencing Factors of Population Dynamics*

After mapping the dynamic patterns of population growth, we confirmed the spatial associations between the rank of cities and the growth of population in the YRD. Table 2 shows the modeling results in detail. A positive and significant correlation exists between economic gains (i.e., GDP and employ) and population (both the total and growth size). Facilities and public services (i.e., bed and edu) are also positively related to the total population size. However, influences of other variables on total population and growth size vary across time, indicating a temporal heterogeneity of residents' concerns about urban amenities. Similar to Maslow's hierarchy of needs, economic gains can here be considered as physiological needs and are always important for population growth. Social and natural amenities including Internet accessibility and urban green space—as higher-level needs—did not matter for growth until the turn of the new millennium. For the negative factors, the 'crowding-out effect' of living costs and environmental pollution are not significant, as theoretically expected, suggesting that residents tend to care more about development opportunities than the negative impacts of living in high-ranking cities. In addition, the coefficient of cities' ranking in terms of population (both the total and growth size) vary across time as well. In the 1990s, the coefficient was insignificant, which indicates that the agglomeration of population was not necessarily in high-ranking cities and is in line with the rise of medium and small cities. In the recent two decades, the coefficients of rank for total population become significant, suggesting a positive relationship between population and urban hierarchy, well reflecting the booming and popularity of large cities. Notably, the coefficient of rank for population growth is significantly negative in the last decade. The result further demonstrates that although most population growth still occurred in large cities, the growth rate of population decreased.

Table 2. Results of regression models.

Variables		1990–2000		2000–2010		2010–2020	
		Total	Growth	Total	Growth	Total	Growth
Economic amenity	GDP	0.412 ***	0.379 ***	0.121 ***	0.12 ***	0.147 ***	0.068 ***
	employ	0.216 ***	0.336 ***	0.091 ***	0.101 ***	0.099 ***	0.368 ***
	livexp	−0.083 **	0.065	−0.005	0.069 ***	0.004	0.075
	hp	0.076 ***	0.049	0.047 ***	0.027 ***	0.056 ***	0.036
Social amenity	*bed*	0.186 ***	0.12	0.138 ***	0.122 ***	0.127 ***	0.067 **
	edu	0.101 ***	−0.055	0.146 ***	0.089 ***	0.146 ***	0.046 ***
	FDI	−0.087 *	−0.155	0.087 ***	0.213 ***	0.021 *	0.023
	inter	−0.105	−0.024	0.12 ***	0.021 **	0.151 ***	0.11 ***
Natural amenity	*pm*2.5	0.102 ***	0.081	0.065 ***	−0.021	0.047 ***	−0.068
	green	−0.045	−0.106	0.148 ***	0.174 ***	0.168 ***	0.096 ***
Control	*rank*	0.331	0.829	1.642 ***	0.186	2.211 ***	−1.099 **
Constant term		−0.02	−0.073	−0.018	−0.034	−0.027	−0.017
Observation count		233		213		193	
Adjusted R^2		0.837	0.395	0.975	0.939	0.991	0.812
F value		19.861	3.396	315.579	125.786	534.671	22.787

Note: ***, **, * denote statistical significance (p value) of 1%, 5%, and 10%, respectively.

3.2.1. Economic Amenity

Economic gains play a positive role in both total population and growth of population, while the coefficients of cost variables are different. This is partly because cities with higher income and more job opportunities tend to be good for population growth. By 2010, the coefficient of GDP decreases with that of employ increasing. It implies that economic gains initially predominated but then gave way to non-marketing factors, when people focused more on quality of life. For the impact of living costs, the coefficient for total population size is significantly negative in 2000, suggesting that high costs can to some extent impede the growth of population. This well explains the rise of small and medium cities in the 1990s. Inconsistent with our expectation, the coefficients of house prices to total population size are significantly positive. This can be attributed to the small ratio of house purchases in big cities. Tenants do not have to pay down-payments and mortgages, which makes the 'crowding-out effect' of skyrocketing house prices insignificant. However, for the growth of population, the coefficient of living costs is significantly positive in 2010. It confirms the argument by Carlino and Saiz that economic gains rather than economic costs are the main determinant of residential choice [55].

3.2.2. Social Amenity

Facilities and public services can largely drive population to gather in large cities but have different impacts on total population and growth of population. In 2000, the coefficients of healthcare and education for population growth are insignificant, suggesting that public services had not become the main factors in people's choice of location. Although public services in large cities are attractive, most migrants are excluded from healthcare by the hukou system [56]. By 2010, the coefficient of facilities and public services for population growth became significantly positive, implying that residents were increasingly concerned about social welfare [16]. This can also be evidenced by the fact that people were attracted to larger cities with the agglomeration of public services. During 2000–2010, the total population in the YRD increases by approximately 37.92 million, including 36.09 million in large cities and mega/major cities, accounting for 95% of the population increase. Public services have the same trend in large cities: 87% of the increase in hospital beds in the YRD and more than half of new investment in education are concentrated in large cities. By 2020, the coefficient of public services for total population is stable, while for population growth, it decreases. The improvement of public services is becoming attractive for people gathering in large cities, but its influence on population growth has tended to decrease. That is partly because the inequality of public services across urban hierarchy narrows under the integration of the Yangtze River Delta, which promotes the sharing of inter-province and inter-city healthcare and education.

With respect to the impact of social atmosphere, the authors argue that a welcoming atmosphere does not necessarily lead to population growth. As Table 2 shows, the coefficient of openness to the global market for the total population is negative ($p < 0.1$), and the correlation between Internet accessibility and total population is insignificant in 2000. This may be related to the fact that China had not yet joined the World Trade Organization (WTO) [57]. By 2010, the two coefficients become significantly positive, indicating that cities with higher openness have larger population growth. By 2020, the positive impact of openness to the global market on the total population size diminishes, while the impact of Internet accessibility increases. This may be due to the adjustment of the international production structure and the rise in transaction costs in recent years; the impact of FDI on population growth becomes less significant. However, in the era of COVID-19, there is more contracting-out of tasks, more provision of services over a distance, and more sales to distant world markets. Therefore, the impact of the Internet on the total population has become more significant.

3.2.3. Natural Amenity

As shown in Table 2, green space has no significant relationship with total population or population growth in the 1990s, indicating that people cared less about the environment than economic opportunities in the first half of the urbanizing era. Since the turn of the new millennium, however, green space has become positively associated with population size in terms of both total amount and growth. This well echoes the finding by Shen et al. [47] that environmental facilities are nowadays important considerations for residents to choose locations in which to settle. For the coefficients of PM2.5, the hypothesis that the air population has a 'crowding out effect' on the total population fails to pass the test. Rather, the gathering of a population in cities with more opportunities generates a positive relationship between population size and air pollution (*pm*2.5). This can also be demonstrated by metropolises, such as London, Detroit, and Beijing, being the most popular cities in their corresponding countries, with no regard for their heavily polluted nature [58]. With regard to the impact on population growth, the coefficient of PM2.5 changes from positive in the 1990s to negative in the 2010s. The inhibitory effect of air pollution on population growth, coupled with the aforementioned impact of green space, indicates that people increasingly care about their physical health and then about natural amenities with the advancement of the society. As a sign of the awakening of citizens' environmental awareness, this can also be attributed to the widespread coverage of environmental pollution hazards in recent decades.

4. Discussion and Conclusions

4.1. Discussion

Our findings have the following implications for the literature and for urban development strategies. First, urban amenities have gradually played a critical role in attracting people to live and work in cities. Such a finding is similar to the "consumer city" argument [33], where urban amenities rather than agglomeration economies attract people. Slightly differently, we find that economic gains are always important for population growth. Our finding suggests that the driving factors of population growth across urban hierarchy have gradually changed from economic factors to both economic and amenity factors. Second, our findings contribute to the fields of economic geography regarding polycentricity. This study explains the reasons for population growth in terms of the population's (consumers') choices of cities of different ranks. It contributes to the polycentric urban development literature, which traditionally attributes the benefits of polycentric urban development to the facilitation of agglomeration economies in terms of production [25].

To promote urban population growth, the above problems should be solved as an initial step. First, it is better to improve the natural amenities of the city. The authors find that environmental facilities are nowadays important considerations for residents when choosing locations in which to settle. For urban planners and governors, gradual reductions in air pollution and increased urban green space will be key to making a city more attractive to people. Second, megacities and major metropolises ought to gradually share public service resources with small and medium cities. The results demonstrate that facilities and public services can largely attract people to large cities, while public resources and favorable policies tend to polarize toward large cities in reality. In contrast, small and medium cities are in a disadvantageous position, with insufficient facilities and public services. Therefore, it is important to establish a cross-regional and urban sharing mechanism for public services. By this means, the attractiveness of small and medium cities could be effectively enhanced, where the population can enjoy the same facilities and public services. Third, urban amenities should meet the various needs of different groups. The findings suggest that low-income groups may care more about the city's economic affordability, while high-income groups seem more interested in the city's natural amenities and social atmosphere. For low-income groups, we should focus on providing adequate employment opportunities and public rental housing; for high-income groups and creative classes, we should pay more attention to providing a diverse and shared cultural environment and leisure space.

4.2. Conclusions

In this paper, we investigated population dynamics across urban hierarchies and its determinants in the Yangtze River Delta (YRD). The results imply that the YRD has witnessed an upward tendency of population dynamics, though the growth rate of populations in high-ranking cities declined recently. Specifically, the Yangtze River Delta witnessed a rise in medium and small cities in the 1990s, as the county-level cities had taken the lead in the transition from centrally planned economies to a market-driven economy. With the intensification of globalization and agglomeration of economic activities in large cities and emerging megacities, an unprecedented population explosion has occurred in the YRD since the turn of the new millennium. In the 2010s, the majority of population growth was still concentrated in large cities, while the growth rate in megacities decreased. Geographically, we find an emerging reversal from centripetal gathering (i.e., population declines in cities in the vast peripheries and increases in the core) to outward overflow (i.e., the geographic extent of cities with population growth shrinks first and thereafter expands) in the recent trend of population dynamics.

To shed further light on the impetus of population dynamics, the authors proposed a framework of urban amenity and found that i) concerns of residents in choosing cities in which to settle gradually changed from economic opportunities to multidimensional amenities, and ii) the influencing mechanisms vary across time. That is, slightly different from Glaeser's consumer cities, economic gains, as physiological needs, are always important for population growth. Social and natural amenities including Internet accessibility and urban green space, as higher-level needs, did not affect growth until the turn of the new millennium. In terms of negative factors, the 'crowding-out effect' of living costs is not significant, as theoretically expected, suggesting that residents tend to care more about development opportunities rather than the negative impacts of living in high-ranking cities. However, the negative coefficient of environmental pollution for growth in the new century, coupled with the positive influence of green space, indicates that people increasingly care about their physical health and then about natural amenities with the advancement of the society. In addition, the coefficients of public services and social atmosphere become significantly positive, suggesting that social amenities matter for the development of the population.

Finally, this study could be improved in the future by more fully taking into account the floating population. As the natural population growth drops, the floating population is a supplement to the increase in the total population of high-ranking cities. Moreover, we have not considered the impact of policy and strategy, such as urban development policy, transport infrastructure development, and talent introduction policy. Taking the political factors into consideration may potentially further improve our understanding of the impetus underlying population dynamics.

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Data Availability Statement: The census data for 2000–2010 are publicly available from the National Bureau of Statistics of China (http://www.stats.gov.cn/, accessed on 1 July 2021). The 2020 census needs to be obtained by consulting the Seventh Census Bulletins issued by local governments in China, which can be found online at: https://tjgb.hongheiku.com/%e4%b8%ad%e5%9b%bd, accessed on 1 July 2021. The "China County Statistical Yearbook 2001–2021" can be obtained through the China National Knowledge Infrastructure (https://data.cnki.net/yearbook/Single/N2022040099 accessed on 1 July 2022). The data on house prices are available at: https://nanjing.anjuke.com/; https://www.sciengine.com/JGCDD/doi/10.3974/geodp.2019.04.09;JSESSIONID=acc2fa5c-d17b-4230-9f53-e61df23d12a4, accessed on 1 July 2021.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Spatio-Temporal Evolution and Influencing Factors of Open Economy Development in the Yangtze River Delta Area

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Abstract: Since economic globalization is unstable, it is difficult for the traditional open economic development model to meet the requirements of China's development, and there is an urgent need for new ideas and models to be reoriented. Based on the analysis of the development mechanism of China's open economy at this stage, we used the entropy method, Theil coefficient, Gini coefficient, and spatial Durbin model (SDM) to analyze the spatio-temporal pattern and influencing factors of the high-quality development level of the open economy in the Yangtze River Delta Area (YRDA). The results indicated that during the study period, the development level and development difference of open economy were on the rise, and the spatial difference in different regions was significant. The development of open economy was affected by many factors, and there was a spatial spillover effect. Based on the existing problems, at the stage of high-quality economic development, the YDRA should seize the opportunities brought by the new development pattern, improve government services, optimize innovation drive, and promote the development of open economy to a higher level. We believe that the results of this study can also provide relevant experience for the development of open economy in other regions of China.

Keywords: open economy; spatio-temporal evolution; influencing factors; Yangtze River Delta Area

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1. Introduction

Under the background of economic globalization, the political, economic, and cultural ties between countries in the world have reached a close degree unprecedentedly, providing a good environment for developing the open economy [1]. Under the guidance of Adam Smith and David Ricardo's theory of the international division of labor and theory of comparative advantage, countries give full play to their comparative advantages to actively participate in the international division of labor, promote the more effective allocation of resources among countries and regions, improve labor productivity, and create the driving force for economic development [2]. Since the reform and opening up policy was implemented, China has continuously deepened its opening up to the outside world. Then, China's rapid development was maintained, and other countries simultaneously provided opportunities for joint action. However, with the impact of the international ideological trend of "Anti-globalization" and the competition in the international market becoming more and more fierce, the COVID-19 epidemic has led to an increase in the risk of the global financial crisis and significant changes in the world economic and trade order and pattern, which have brought significant challenges to the development of China's opening up to the outside world [3].

The open economy has always been one of the essential issues paid attention to by academic circles. The current study on the development of the open economy is mainly focused on the connotation of the development of the open economy [4,5], evaluation of development level [6–8], influencing factors [9–11], and so on. Specifically, there are two main arguments about the connotation study. One is that an open economy is an export-oriented economy [12,13], and the other is that an open economy is a strategy in which export orientation and import substitution coexist [14]. However, China's understanding of the connotation of the open economy is mainly affected by policies [15], which are integrated with China's national conditions based on learning from relevant foreign theories. In the early stage, the measurement of the development level of an open economy was replaced by a single measurement of trade openness [16] or capital openness [17], that is, it was measured directly by the degree of dependence on foreign trade or the degree of convergence of relative prices. As De. Lombaerde [18] proposed that the measurement of the development level of the open economy should comprehensively consider many factors, such as trade development and system reform, the construction of the index system tends to be diversified gradually. The study methods mainly involve quantitative evaluation methods such as the DSGE model [19], entropy weight TOPSIS [20], grey correlation model [21], and dynamic factor analysis [22]. It can be seen that there is not a unified understanding of the evaluation index system and evaluation methods of the open economy, and most scholars choose the corresponding evaluation indicators and measurement methods based on the actual situation of the study object, which provides a good reference for the construction of open economy evaluation in this study. As for the study of influencing factors, scholars at home and abroad continue to enrich them from both theoretical and empirical study and analysis through the ideology of cross-sectional data and multiple regression [23,24], but the consideration of spatial factors has not been taken into account, and there is a lack of analysis on regional heterogeneity and spatial spillover effects.

Via academic study, the multi-dimensional perspective of open economy analysis was expanded [25–27], and a powerful way is provided for an in-depth understanding of the development pattern of the open economy and its driving forces. The existing problems in the relevant research also provide a new direction for the development of this study. Apart from the above issues, most existing research focuses on the development of the past open economy. But as China's economy moves from a phase of rapid growth to a phase of high-quality development, and driven by the "Double-cycle" development strategy, China's open economy development has been transformed from a traditional "Quantity-driven" model to an "Innovation-led" model of high-level development [28,29]. Under such conditions, what are the changes in the development mechanism of China's open economy? What are the ways to promote the effective development of an open economy? These are the vital issues that we need to think about [30]. Moreover, because of the influence of the spatial variability of the research objects, the policy recommendations put forward by the previous research have problems of weak universality and insufficient pertinence, which cannot effectively reflect the overall characteristics of China's open economic development. The YRDA is one of the core regions with the most active economic development, vital openness, and innovation ability in China. It is the most representative region in the development process of China's open economy and plays a vital role in China's opening-up strategy [31]. Therefore, starting from the new environment of China's open economic development, based on the discussion of the development mechanism of China's open economy at the present stage, this paper selects three provinces and one city in the YRDA as a case study to analyze the space-time pattern and influencing factors of its open economic development level, and then finds out the problems and proposes solutions. We hope that it can provide a reference basis for enhancing the competitiveness of the YRDA in the domestic and international cycle, promoting regional integration, speeding up the development of a higher-level open economy, and providing the relevant experience for the development of open economy in other regions of China.

The paper is arranged as follows. The second part discusses the mechanism of development of the open economy, the third part introduces the study regions and methods, and constructs the evaluation index system of comprehensive development level in combination with the meaning of open economy. The fourth part analyzes the empirical results. The fifth part discusses the results of the analysis, and the sixth part summarizes the results and points out the study's shortcomings.

2. Development Mechanism of Open Economy

2.1. The Definition of Open Economy

The open economy is an economic model that allows the free cross-border movement of all factors and products, unlike a closed economy [32]. In an open economy, factors, goods, and services can move more freely across borders to achieve optimal allocation of resources and maximum economic efficiency [33]. The open economy mainly includes base, scale, structure, and benefit. It emphasizes linking the domestic economy with the whole international market, participating in the international division of labor as fully as possible, and giving play to the comparative advantage of the national economy in the International Division of Labor. In the trend of economic globalization, countries have lowered tariff barriers to promote the free flow of capital, making a significant development of the open economy [34].

2.2. Development Mechanism of Open Economy

In the past, China's open economy mainly realized "High-speed" growth by expanding the scale of low-end factor input, blindly expanding production capacity, pursuing the volume of goods exports, and introducing foreign investment [35]. However, this extensive development model has not only caused a series of problems, such as environmental pollution, waste of resources, low efficiency, and so on, but it is also difficult for the traditional development model of the open economy to meet the new needs of China's socio-economic transformation and upgrading and opening-up strategy and adapt to the new pattern of the global industrial division of labor [36]. The new development model of an open economy emphasizes a steady growth tone, starting with the interaction between supply and demand, interconnection, innovation-driven, industrial structure, regional coordination, and other aspects, and drives the Omni-directional upgrading of the scale of open economy, the foundation of open economy, potential of open economy, the quality and efficiency of open economy, to realize the virtuous circle of economic development and the promotion of international competitiveness [37]. Given this, this paper focuses on the four main focal points of the scale of open economy, the foundation of open economy, the potential of open economy, the quality and efficiency of open economy to analyze the development mechanism of the open economy through the mechanism transmission of domestic and international "Double cycle" new development pattern, scientific and technological innovation, and attracting foreign investment (Figure 1).

2.2.1. The Mechanism of Action of the New Development Pattern of "Double Circulation" on the Development of Open Economy

Under the new situation of a sharp decline in external demand caused by the global epidemic, speeding up the construction of a new development pattern of domestic and international "Double cycle" is an effective way to promote the high-level development of an open economy [38]. China takes the great domestic cycle as the main body, starting with the domestic market demand structure and product supply structure, and combines the strategy of expanding domestic demand with deepening supply-side structural reform to form a high-level dynamic balance of order pulling supply and supply, creating demand. This measure has effectively stimulated the economic vitality of the country's interior and laid the foundation for the efficient development of an open economy. Meanwhile, China has seized the opportunity of the development of the international cycle, actively carried out foreign economic and trade cooperation, docked high-standard international economic and trade rules, and continued to participate in the international division of labor through the implementation of the "Belt and Road Initiative" strategy to strengthen connectivity and coordinated development with countries along the Road, and maximize the scale of opening up to the outside world.

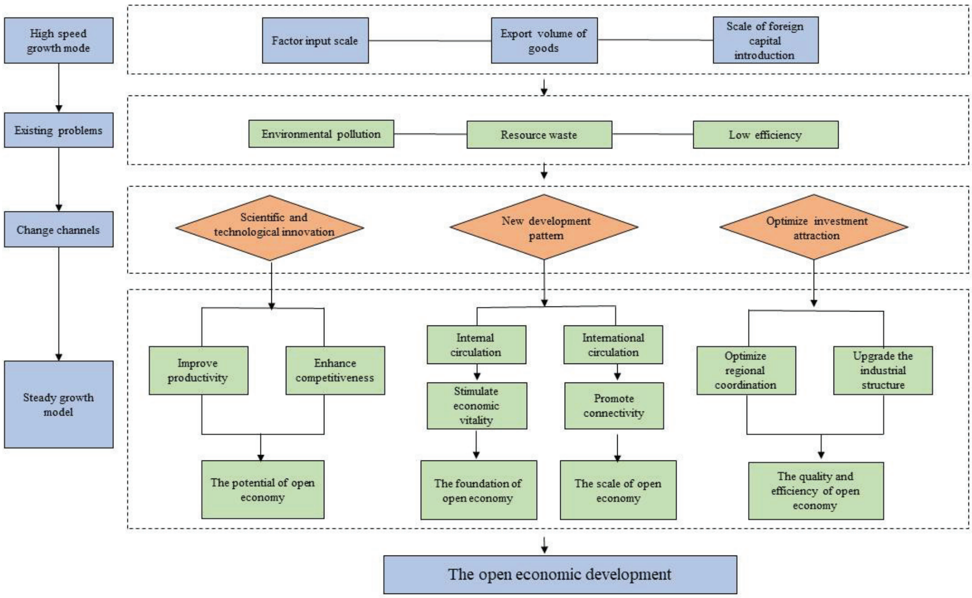

Figure 1. Mechanism map for the development of the open economy.

2.2.2. The Mechanism of Action of Scientific and Technological Innovation on the Development of Open Economy

Under the invasion and attack of the wave of anti-globalization, if China wants to get rid of the dilemma that others control vital industries and technologies, the core is to persist in using scientific and technological innovation to promote the development of an open economy. On the one hand, scientific and technological innovation maximizes production efficiency through accelerating enterprise process iteration and improving the utilization efficiency of various resource elements and injects new vitality into the growth of the open economy. To this extent, scientific and technological innovation is an important driving force for promoting the transformation and upgrading of an open economy. On the other hand, persisting in taking scientific and technological innovation as the forerunner can provide new comparative advantages for market products, achieve Omni-directional quality improvement, help continuously tap the potential of the open economy, and promote the development of an open economy.

2.2.3. The Mechanism of Action of Investment Attraction on the Development of Open Economy

Investment attraction plays an important role in improving the quality and efficiency of an open economy [39]. Due to the obvious gradient differences in the level of economic development among regions in China, there is still a large gap in the quality and degree of openness between inland areas and the eastern coast, which to a certain extent, hinders the development of the open national economy. By using a reasonable way of investment attraction, the eastern region and even international superior resources will be transferred to inland areas through chambers of commerce and investment to win more development opportunities and promote a higher level of opening up under the premise of promoting coordinated regional development. In addition, the reasonable use of foreign capital can effectively make up for the capital and technological shortcomings of domestic industrial product, promote the transformation and upgrading of industrial structure, and then guide local enterprises to show strong competitiveness in the international market to provide support for the high-quality development of an open economy.

3. Materials and Methods

3.1. Selection of Study Area

According to the "Outline of the YRDA Integrated Development Plan" officially issued by the State Council in December 2019, the YRDA was planned to cover all four provinces and cities of Suzhou, Zhejiang, Anhui, and Shanghai, with a total of 41 cities. It is an alluvial plain formed before the Yangtze River enters the sea, located in the lower reaches of the Yangtze River in China, bordering the Yellow Sea and the East Sea and at the place where the rivers and the sea meet, with many coastal ports along the river. As of the end of 2019, it played a pivotal strategic role in the overall national modernization and all-round opening pattern as one of the most active, open, and innovative regions in China, with a population of 227 million and a regional area of 358,000 square kilometers (Figure 2).

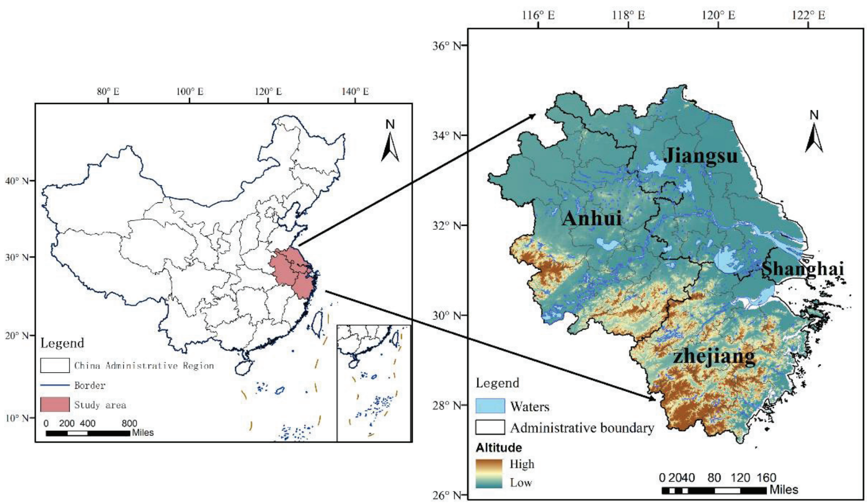

Figure 2. The study area.

3.2. Research Methods

3.2.1. Measurement of Open Economy Development Level

This study adopted the entropy method to measure the level of open economy development in the YRDA, which can reduce the artificial subjective influence in determining the weights and improve the objectivity of the attached consequences to obtain more scientific results. Moreover, it reflects the rate of change of sample data by the calculated information entropy, determines the weight according to the order of the information contained in each index, and then calculates the total score [40]. The formulas are as follows:

Standardization of positive indicators:

$$x'_{ij} = \left[\frac{x_{ij} - \min(x_{1j}, x_{2j}, \cdots, x_{nj})}{\max(x_{1j}, x_{2j}, \ldots, x_{nj}) - \min(x_{1j}, x_{2j}, \ldots, x_{nj})} \right] \tag{1}$$

Standardization of negative indicators:

$$x'_{ij} = \left[\frac{\max(x_{1j}, x_{2j}, \ldots, x_{nj}) - x_{ij}}{\max(x_{1j}, x_{2j}, \ldots, x_{nj}) - \min(x_{1j}, x_{2j}, \ldots, x_{nj})} \right] \tag{2}$$

where x'_{ij} refers to the value of the jth indicator in unit i and x'_{ij} is still denoted as x_{ij} in this study.

Calculation of the ratio:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{3}$$

Calculation of the entropy:

$$e_j = -k\sum_{i=1}^{n} p_{ij} \ln\left(p_{ij}\right), k > 0, k = \frac{1}{1n(n)}, e_j \geq 0 \tag{4}$$

Calculation of the variance coefficient:

$$g_j = \frac{1 - e_i}{m - E_e} \text{ , } E_e = \sum_{j=1}^{m} e_i \text{ , } 0 \leq g_j \leq 1 \text{ , } \sum_{j=1}^{m} g_i = 1 \tag{5}$$

Calculation of the weight:

$$w_i = \frac{g_i}{\sum_{j=1}^{m} g_i} \quad (1 \leq j \leq m) \tag{6}$$

Calculation of the total score:

$$s_j = \sum_{j=1}^{m} w_j * p_{ij} \quad (i = 1, 2, \cdots, n) \tag{7}$$

3.2.2. Methods of Spatial-Temporal Variance Analysis

Range and standard deviation: Range and standard deviation are commonly used statistics to describe the degree of data dispersion. The range can reflect the fluctuation range of data, while standard deviation can represent the precision of data. The combination of the two can help us have a more comprehensive understanding of the changes in the level of open economic development in the YRDA. Therefore, in this study, the range (R) and standard deviation (σ) were used to reflect the absolute differences in the level of open economy development in the YRDA. The formulas are as follows:

$$\begin{gathered} R = X_{max} - X_{min} \\ \sigma_t = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_i - \overline{x})^2} \end{gathered} \tag{8}$$

where R refers to the absolute differences in the level of development of the open economy; X_{max} is the maximum value; X_{min} is the minimum value; σ refers to the standard deviation of the level of open economy development in year t; n refers to the number of municipalities in the YRDA; $\overline{x}$ refers to the average level of development; X_i is the level of open economy development in the i municipal area.

Coefficient of variation: Given the apparent differences in the population of each city in the YRDA, the coefficient of variation, as a dimensionless quantity, is more objective and practical when comparing data with different dimensions or mean values [41]. Therefore, this study selected the population-weighted coefficient of variation to measure the relative differences in open economic development among the municipalities in the YRDA, which is calculated as:

$$CV_w = \sqrt{\sum_{i=1}^{n} \left(X_i - \overline{X}\right)^2 (p_i/p)} / \overline{X} \tag{9}$$

where CV_w refers to the coefficient of variation; p_i refers to the population in municipality i; and p is the total population of the YRDA.

Gini coefficient: In view of the objective reality that there will be a particular gap in the development of each indicator system in an open economy, the Gini coefficient can give the quantitative limit of the difference degree of each indicator, thereby more intuitively reflecting the development gap between the indicators [42]. Therefore, the Gini coefficient was used to analyze the development differences of various indicator systems in the open economy of YRDA and their contributions to the difference in overall development level, which is calculated as:

$$\begin{gathered} G = \sum G_d^* S_d \\ G_d^* = 1 - \frac{1}{g}\left(2\sum_1^{g-1} W_g + 1\right) \end{gathered} \quad (10)$$

where G refers to the total Gini coefficient of open economy development; G_d^* represents the sub-Gini coefficient of each indicator system; S_d represents the ratio of the development level score to the total score of the subsystem of the d-indicator system in open economy development; g is the number of groups; W_g refers to the ratio of the open economy development level score of group g to the total score of the study area; the percentage contribution of the d-indicator system subsystem to the overall Gini coefficient is $G_d^* * S_d/G \times 100\%$.

Thiel coefficient: Theil coefficient can measure the proportion of the intra-group gap and the inter-group gap in the total gap and subdivide inter-regional gap and intra-regional gap, thus providing a basis for finding the main factors of regional gap change [43]. Therefore, the Thiel coefficient was used to measure the inter-regional and intra-regional differences in the level of open economic development in the YRDA, which is calculated as follows:

$$\begin{gathered} T = T_{inter-regional} + T_{intra-regional} = \\ \sum_k \frac{X_k}{X} \ln\left(\frac{X_k/X}{P_k/P}\right) \sum_k \frac{X_k}{X} \left[\sum_i \frac{X_{ki}}{X_k} \ln\left(\frac{X_{ki}/X_k}{P_{ki}/P_k}\right)\right] \end{gathered} \quad (11)$$

where T refers to the Theil coefficient of the open economy development level in the study area; X represents the level of open economy development; X_k represents the level of open economy development in region k; X_{ki} is the level of open economic development of study unit i in region k; P refers to the total population of the study area; P_k refers to the population of region k; P_{ki} is the population of study unit i in region k; the proportion of intra-regional and inter-regional contributions are $\frac{T_{inter-regional/intra-regional}}{T} * 100\%$; the proportion of contribution from region k is $\frac{T_k}{T_{intra-regional}} * 100\%$.

Spatial autocorrelation: Moran′s I is usually used to judge whether there is a correlation between spatial entities within a certain range. Therefore, we used Moran′s I to measure the spatial agglomeration characteristics of the open economy development level in the YRDA and estimated its statistical significance by calculating the z-score and p-value. Generally, it takes values in the range of −1 to 1, while larger absolute values represent larger spatial correlations [44]. The equation is as follows:

$$\text{Moran's I} = \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij}(X_i - \overline{x})(X_j - \overline{x})}{\sigma^2 \sum_{i=1}^n \sum_{j=1}^n w_{ij}} \quad (12)$$

where $\sigma^2 = \frac{1}{n}\sum_{i=1}^n (X_i - \overline{x})$; $\overline{x} = \frac{1}{n}\sum_{i=1}^n X_i$; X_i and X_j represent the level of open economy development in study unit i and study unit j; w_{ij} is the spatial weight matrix.

The degree of its local spatial association and distribution pattern could be further measured with the help of I_i, which is calculated as:

$$I_i = z_i' \sum_j w_{ij} z_j' \quad (13)$$

where z_i' and z_j' represent standardized observations, and other variables have the same meaning as before.

3.2.3. Method of Influencing Factors Analysis

Based on the reality of unbalanced spatial development in the YRDA, we need to consider the heterogeneity between different regions when investigating the influencing factors of open economic development, so the SDM was used to conduct the analysis [45]. The equation is as follows:

$$Y_{it} = C + \rho \sum w_{ij} Y_{it} + X_{it}\beta + \delta \sum w_{ij} X_{it} + \mu_i + \theta_t + \epsilon_{it} \quad (14)$$

where Y_{it} represents the variable responding to the level of open economy development; C refers to the constant term; $\rho \sum w_{ij} Y_{it}$ refers to the spatial lag term of the explained variable; ρ is the lag term coefficient; X_{it} refers to the explanatory variable; $\delta \sum w_{ij} X_{it}$ represents the spatial lag term of the explanatory variable; δ represents its spatial lag term coefficient; w_{ij} is the spatial weight matrix, and nested matrices were constructed for each interval with reference to Hao et al. [46] and Xue et al. [47] (Table 1); λ is the lagging factor of the perturbation term; μ_i represents the fixed effect of a region; θ_t represents the fixed effect of time.

Table 1. Weight matrix description.

Spatial Weight Matrix	Meaning	Formula	Explanation
Adjacency Weight Matrix W1	The provinces are geographically adjacent to each other	$w_1 = \begin{cases} 0 \\ 1 \end{cases}$	0 represents no connection between two regions, 1 represents the connection between two areas
Economic distance Weight Matrix W2	The economic gap between the provinces	$w_2 = \frac{1}{\lvert P_i - P_j \rvert} \times \frac{1}{d_{ij}}$	P_i and P_j represent the average of real GDP per capita between province I and province j over the sample period, d_{ij} is the geographical straight-line distance of each provincial capital city.
Nested Weight Matrix W3	The geographical proximity and economic gap between the provinces	$w_3 = w_1^* w_2$	The product of the adjacency matrix and the economic matrix

3.3. The Construction of the Indicator System and Selection of Variables

3.3.1. Indicator System Construction

At present, the evaluation index system of open economy development is being enriched and developed as the research progresses, which is mainly reflected in the development of domestic and foreign scholars from one or a few indicators to a comprehensive evaluation index system with richer and more diverse perspectives and distinctive indicators [48,49]. Based on the analysis of the development mechanism of the open economy in the second part, combined with the existing research results [20,21,50], based on the principles of scientific, systematic, operability, and comparability, the index system is constructed from the four levels of the foundation, scale, quality and efficiency, and potential of the development of the open economy, with 20 secondary indicators (Table 2).

Table 2. Comprehensive evaluation index system of development level of open economy in YRDA.

First-Level Indicators	Secondary Indicators	The Meaning of Indicators	Unit
The foundation of open economy	GDP per capita	Regional GDP / total regional population	Million yuan
	The proportion of secondary and tertiary industries	Secondary industry output/regional GDP	%
	Human capital level	Number of people in scientific services, technical exploration / total regional population	%
	Fixed asset investment per capita	Regional fixed asset investment amount / total regional population	Million yuan
	Urbanization rate	Urban population / total regional population	%

Table 2. *Cont.*

First-Level Indicators	Secondary Indicators	The Meaning of Indicators	Unit
The scale of open economy	Foreign trade volume	Total import and export	Billion
	Domestic trade volume	Total retail sales of social consumer goods	100 Million yuan
	Amount of foreign direct investment	Actual utilization of foreign investment	Billion
	Foreign trade dependence	Foreign trade in goods/regional GDP	%
	Foreign investment dependence	Actual foreign direct investment/regional GDP	%
The quality and efficiency of open economy	Trade economic contribution	(Total retail sales of social consumer goods + total exports-total imports)/regional GDP	%
	The net export contribution rate	Increase in net exports / increase in GDP	%
	Share of international tourism revenue	Tourism foreign exchange earnings / regional GDP	%
	Contribution of foreign investment	FDI / social fixed asset investment	%
	The proportion of foreign-invested enterprises	Number of foreign-invested enterprises/number of industrial enterprises	%
The potential of open economy	Fiscal expenditure to GDP ratio	Fiscal spending/regional GDP	%
	Share of expenditure on science and education	Expenditure on science and education / total regional financial expenditure	%
	Number of invention patents per 10,000 people	Number of granted invention patent applications/total regional population	Piece
	The proportion of total post and telecommunication business in GDP	Gross postal and telecommunications business/regional GDP	%
	Internet penetration	Number of Internet users	Door

(1) The foundation of open economy

The foundation of open economy is an important support to realize the development of an open economy and also an indispensable factor in introducing foreign capital, expanding trade, and promoting economic growth [20]. Among the selected indicators, the GDP per capita index is an important indicator to measure the status of regional economic development. The higher the GDP per capita, the stronger the development foundation of the Open economy. The index of the proportion of the secondary and tertiary industries can reflect the degree of the regional industrial structure, and the index of the level of human capital is a sign of the strength of the scientific and technological strength of the regional economic development. The level of fixed asset investment per capita can reflect the ability of local people to invest, and the urbanization rate reflects the regional urbanization by country.

(2) The scale of open economy

The scale of open economy is a vital aspect in evaluating the development of an open economy [51], which measures the foreign trade capacity of a region from the perspective of quantity and makes the accumulation of quantitative change for the qualitative change of an open economy. Among the selected indicators, the volume of foreign trade and the importance of domestic trade indicate the size of the region's capacity for foreign and domestic trade. The degree of dependence on foreign trade and foreign investment is the index to reflect the degree of influence of trade activities on regional economic development and the degree of dependence on foreign capital constituted by gross domestic product, the size of the foreign direct investment reflects the region's ability to attract foreign investment.

(3) The quality and efficiency of open economy

The quality and efficiency of open economy is an important aspect of evaluating the effectiveness of open economy development, which measures the foreign trade of a region from a qualitative perspective [51]. Meanwhile, it emphasizes the importance and frontier of quality elements in the open economy development process, effectively improving the opening scale. Among the selected indicators, the contribution of trade economy and foreign investment refers to the impact of trade and foreign investment on the regional economy and fixed asset investment, respectively. The contribution rate of net exports reflects the degree of contribution of trade surplus to the economy and the degree of balance between imports and exports of a region's foreign trade. The proportion of international tourism income reflects the share of foreign exchange tourism income in GDP. The greater the proportion, the greater the role of international tourism in the region's development. The proportion of foreign-invested enterprises refers to the proportion of the number of foreign-invested enterprises in the total number of regional industrial enterprises. The greater the value, the more significant the contribution of foreign-funded enterprises to regional development.

(4) The potential of open economy

The potential of open economy is an essential element in measuring the sustainable development of an open economy and an important indicator to promote the high-level development of an open economy [20]. Among the selected indicators, the ratio of target fiscal expenditure to GDP reflects the government's budgetary support. The proportion of total postal and telecommunications business in GDP and the internet penetration rate are two indicators that reflect the degree of perfection of a region's infrastructure. Financial support from the government and sound infrastructure can provide the impetus for the efficient development of the open economy. The share of expenditure on science and education and the number of invention patents owned by 10,000 people reflect the capacity of science and innovation in a region. Excellent innovation ability and a high level of human capital can effectively promote the development of the open regional economy.

3.3.2. Variables Selection

As the development of the open economy is affected by many factors, this paper, based on relevant research, starts from the six aspects of regional economic strength, industrial structure, social development, scientific and technological level, labor force factors and infrastructure, a total of 10 explanatory variables are selected to explore the influencing factors of Open economy development level in the YRDA [52–55]. The relevant variables are selected as follows.

(1) Explained variable

The explained variable was selected as the values of the open economy development level of 41 municipalities in the YRDA from 2005 to 2019, obtained using the entropy value method and expressed as Y.

(2) Explanatory variables

Regional economic strength is necessary to promote the efficient development of the open regional economy. The more muscular the regional financial stability, the higher the open economy level of development. We choose GDP per capita (X1), a measure of regional economic strength, and fiscal revenue per capita (X2), which represents the range and amount of services the government provides in economic activities, to reflect the regional financial strength.

The industrial structure can reflect the status quo of regional industrial development. Optimizing the industrial system is essential to promoting the development of the open regional economy. We measure the regional industrial structure by the proportion of secondary and tertiary industries (X3). The larger the ratio, the more dynamic the regional economic development is and the more attractive it will be to foreign capital and foreign enterprises.

A stable and harmonious social development is essential for the normal development of open economy activities. We use the urbanization rate (X4), closely related to economic growth, and the per capita retail sales of consumer goods (X5), the most direct reflection of the social consumption demand, to reflect the social development.

The advancement of science and technology can strengthen the division of labor and cooperation among the local open economy in the development process, thereby enhancing the potential of the open economy. Therefore, we use the human capital level (X6) and the ratio of science and technology expenditure to fiscal expenditure (X7) to measure the level of science and technology development.

Infrastructure such as transportation and communications is an indispensable material basis for developing a region's open economy. The traffic condition directly affects the volume of trade and investment. Therefore, we select the size of freight volume (X8) to reflect the traffic situation and the post and telecommunications business volume (X9) to reflect the development of communications construction.

The development of an open economy cannot be separated from the labor factors (X10). In this paper, we choose the sum of employment in the secondary and tertiary industries to reflect the demand for labor.

3.3.3. Data Source and Statistical Description

Based on data updates, the relevant data used to measure the level of open economic development of 41 cities in the YRDA from 2005–2019 are mainly from the China Statistical Yearbook, Shanghai Statistical Yearbook, Jiangsu Statistical Yearbook, Anhui Statistical Yearbook, Zhejiang Statistical Yearbook, statistical yearbooks of each city and statistical bulletins on national economic and social development, with some data coming from the website of the Ministry of Commerce of the People's Republic of China and the statistical bureaus of each urban area.

4. Result Analysis

4.1. The Temporal Evolution of the Development Level of the Open Economy

As seen from Table 3 and Figure 3, the open economy in the YRDA has made significant progress in the past 15 years, and the development level of each city shows a fluctuating upward trend over time, but the absolute differences between cities are growing. Specifically, the variation trend of the range used to characterize the fundamental difference is the same as that of the standard deviation and can be divided into the rapid rising stage of 2005–2010, 2017–2019, and the slow rising stage of 2010–2017, while the change of weighted coefficient of variation is more complicated and goes through three stages: fluctuation rise in 2005–2010, fluctuation decline in 2010–2017 and continuous rise in 2017–2019. Overall, the overall differences in the development level of the open economy in the YRDA showed an expanding trend during the study period.

Table 3. The development level of the Open Economy in YRDA from 2005 to 2019.

City	2005	2010	2015	2019	M	R	City	2005	2010	2015	2019	M	R
Shanghai	0.271	0.467	0.494	0.615	0.435	1	Taizhou	0.044	0.059	0.075	0.090	0.068	22
Suzhou	0.200	0.287	0.329	0.365	0.305	2	Lianyungang	0.054	0.062	0.070	0.075	0.066	23
Hangzhou	0.113	0.186	0.256	0.278	0.209	3	Tongling	0.052	0.069	0.076	0.069	0.066	24
Nanjing	0.124	0.153	0.212	0.263	0.183	4	Huaian	0.033	0.090	0.071	0.088	0.065	25
Ningbo	0.113	0.147	0.195	0.214	0.173	5	Taizhou	0.046	0.054	0.071	0.088	0.065	26
Wuxi	0.105	0.155	0.182	0.213	0.167	6	Lishui	0.035	0.042	0.077	0.066	0.065	27
Changzhou	0.076	0.119	0.149	0.174	0.131	7	Xuzhou	0.031	0.048	0.064	0.088	0.057	28
Jiaxing	0.083	0.101	0.132	0.164	0.122	8	Yancheng	0.029	0.048	0.056	0.077	0.056	29
Nantong	0.080	0.096	0.116	0.124	0.109	9	Bengbu	0.039	0.037	0.065	0.068	0.055	30
Zhenjiang	0.075	0.104	0.107	0.111	0.105	10	Xuancheng	0.030	0.036	0.060	0.068	0.052	31
Huzhou	0.069	0.089	0.107	0.132	0.099	11	Huainan	0.053	0.044	0.057	0.052	0.051	32
Hefei	0.067	0.078	0.103	0.153	0.096	12	Quzhou	0.029	0.036	0.060	0.068	0.046	33
Zhoushan	0.058	0.080	0.141	0.109	0.095	13	Huaibei	0.028	0.039	0.053	0.052	0.045	34

Table 3. *Cont.*

City	2005	2010	2015	2019	M	R	City	2005	2010	2015	2019	M	R
Shaoxing	0.061	0.078	0.117	0.115	0.094	14	Chuzhou	0.021	0.025	0.050	0.062	0.044	35
Jinhua	0.054	0.065	0.096	0.117	0.090	15	Suqian	0.020	0.027	0.062	0.061	0.041	36
Yangzhou	0.058	0.091	0.085	0.108	0.088	16	Lu'an	0.025	0.027	0.047	0.062	0.041	37
Huangshan	0.051	0.071	0.080	0.088	0.079	17	Bozhou	0.019	0.028	0.049	0.055	0.040	38
Wenzhou	0.047	0.055	0.088	0.111	0.077	18	Suzhou	0.021	0.027	0.047	0.068	0.039	39
Wuhu	0.053	0.067	0.090	0.104	0.077	19	Anqing	0.024	0.030	0.037	0.047	0.037	40
Ma'anshan	0.046	0.069	0.084	0.099	0.074	20	Fuyang	0.026	0.029	0.034	0.049	0.036	41
Chizhou	0.042	0.051	0.081	0.085	0.070	21							

Notes: M is the mean value of the development level of the open economy in each region from 2005 to 2019; R is the ranking of the development level of open economy in various regions.

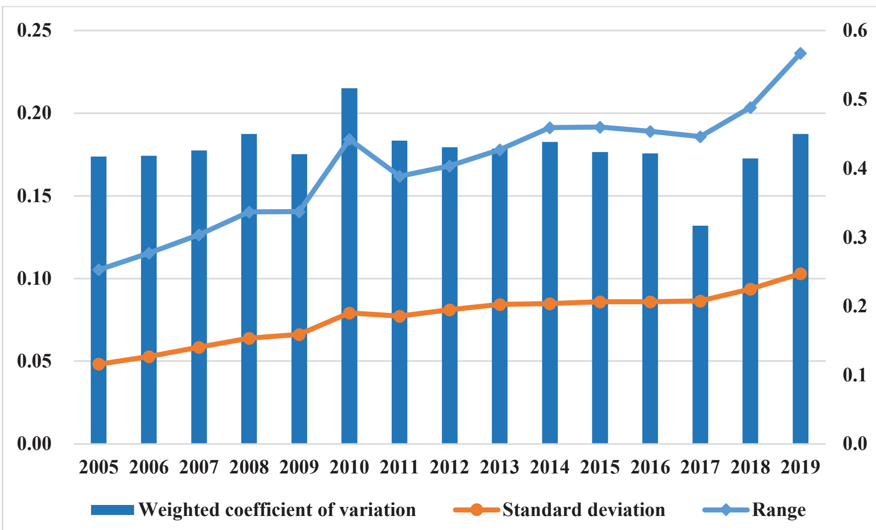

Figure 3. The absolute and relative differences of development level of open economy in the YRDA.

From the point of view of evaluating the four subsystems of the development level of the open economy, the foundation of open economy in the YRDA shows a trend of steady growth, the scale of open economy shows a trend of rising and falling repeatedly. The quality and efficiency of open economy first increase and then decrease. On the whole, the potential of open economy shows a fluctuating upward trend (Table 4). It reflects that the YRDA pays excellent attention to the dimension of the foundation of open economy and potential of open economy, but limited to the bottleneck that open economic structure is unreasonable, it has not effectively realized the coordinated development of quality, benefit, and scale. The Gini coefficient was used to analyze the development differences of each subsystem further. As seen from Table 5 and Figure 4, the overall Gini coefficient of the development level of the open economy in the YRDA from 2005 to 2019 shows a trend of first increasing and then decreasing, indicating that the regional difference shows a fluctuating trend over time. On the whole, the difference in the scale of open economy index subsystem is the main reason for the overall difference in the development level of the open economy in the YRDA, followed by the foundation of open economy index subsystem. Before 2015, the contribution of the open quality and benefits index subsystem to the overall difference is more significant than that of the potential of the open economy index subsystem, and on the contrary, after 2015.

Table 4. The development level of the subsystems of the open economy in YRDA from 2005 to 2019.

Year	FO	SO	QEO	PO
2005	0.679	0.657	0.878	0.291
2006	0.720	0.771	0.928	0.308
2007	0.762	0.903	0.955	0.355
2008	0.811	0.987	0.935	0.378
2009	0.864	0.919	1.100	0.467
2010	0.955	1.069	0.817	0.625
2011	0.978	1.184	0.917	0.631
2012	1.050	1.262	0.918	0.735
2013	1.160	1.305	0.846	0.874
2014	1.234	1.324	0.806	0.876
2015	1.324	1.295	0.771	1.022
2016	1.311	1.297	0.756	1.035
2017	1.166	1.732	1.161	1.623
2018	1.401	1.460	0.683	1.318
2019	1.519	1.508	0.653	1.405

Notes: FO is the foundation of open economy; SO is the scale of open economy; QEO is the quality and efficiency of open economy; PO is the potential of open economy.

Table 5. Gini coefficient of development of open Economy in YRDA from 2005 to 2019.

Year	G	FG	SG	QEG	PG
2005	0.406	0.383	0.619	0.336	0.187
2006	0.407	0.379	0.601	0.336	0.203
2007	0.402	0.376	0.580	0.335	0.190
2008	0.413	0.376	0.577	0.346	0.229
2009	0.423	0.371	0.567	0.412	0.266
2010	0.435	0.374	0.569	0.369	0.384
2011	0.413	0.354	0.563	0.347	0.320
2012	0.405	0.356	0.537	0.341	0.330
2013	0.394	0.350	0.527	0.340	0.306
2014	0.392	0.351	0.533	0.342	0.280
2015	0.399	0.362	0.545	0.358	0.293
2016	0.392	0.345	0.540	0.359	0.291
2017	0.368	0.377	0.467	0.383	0.246
2018	0.388	0.341	0.536	0.371	0.283
2019	0.390	0.343	0.521	0.353	0.318

Notes: G is the Gini coefficient of open economy; FG is the Gini coefficient of FO; SG is the Gini coefficient of SO; QEG is the Gini coefficient of QEO; PG is the Gini coefficient of PO; FO, SO, QEO and PO have the same meaning as before.

4.2. The Spatial Evolution of the Development Level of the Open Economy

Using the natural breakpoint method in Arcgis, the development level of the open regional economy in each year is stratified, and the threshold is rounded. Finally, it is divided into four groups: (0, 0.4] is a low level, (0.4, 0.8] is a secondary level, (0.8, 1.2] is a good level, and more than 1.2 is a better level and spatial distribution map of the development level of open economy in typical years is drawn.

As seen in Figure 5, the spatial differences in the development level of open economy in various cities in the YRDA are noticeable. Still, they show an upward trend overall, and the development level of Huai'an and Taizhou fluctuates wildly, and the development is unstable. In 2019, there were only one low-level city, 15 medium-level cities, 14 good-level cities, and 11 superior-level cities in the YRDA. On the whole, the development level of open economy in the YRDA shows a distribution pattern of "prominent in the middle, high in the south, low in the north, high in the east and low in the west". The level of development of the open economy of cities in the central region is generally higher than that of other cities. The development of Shanghai and provincial capitals such as Nanjing, Hangzhou, and Hefei has been at a high level, maybe because of political and policy advantages. These areas are rich in products, have convenient transportation, rapid economic development, a high level of talent, scientific and technological development, and have certain advantages in the high-quality development of an open economy. From the provincial point of view, the order of the development level of the open economy in various provinces did not change during the study period. Shanghai ranked first, followed by Jiangsu and Zhejiang, and Anhui had the lowest level of development.

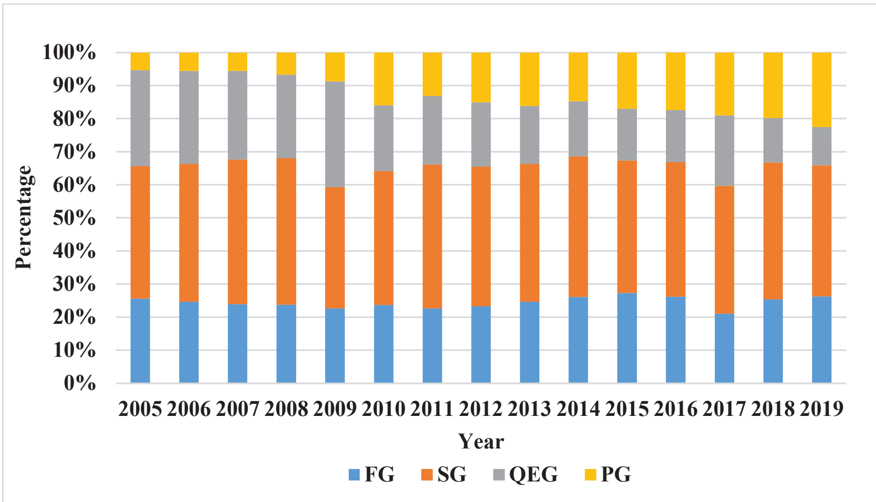

Figure 4. Gini coefficient of development of open economy in YRDA from 2005 to 2019.

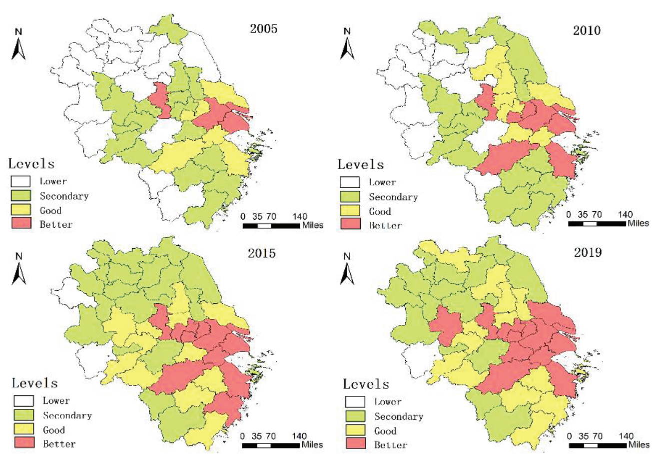

Figure 5. Map of development level of open economy in YRDA from 2005 to 2019.

Theil index is used to study the overall regional differences in the development level of the open economy in the YRDA. According to the geographical conditions, taking the Yangtze River as the boundary, the YRDA is divided into two regions: the north and the south. As seen from Table 6, the overall difference in the development level of the open economy in the YRDA shows a trend of expanding at first and then decreasing. During the study period, the changing trend of the Theil index between regions is the same as that within areas, but the contribution rate of the Theil index within regions shows an upward trend, while that between areas is, on the contrary, indicating that differences within regions are the main realization form of regional differences. From 2005 to 2019, the Theil index of the north and the south fluctuated and decreased, indicating that the regional differences tended to narrow. Except that the contribution rate of the Theil index of the north was lower than that of the south in 2017, the contribution rate of the Theil index of the north was more significant than that of the south in other years. Thus, it can be seen that the north is the main contributor to the widening regional gap.

Table 6. Theil coefficient and its decomposition of development level of open economy in YRDA from 2005 to 2019.

Year	T	TER	TRR	TS	TN	TEC	TRC	TSC	TNC
2005	0.1293	0.0671	0.0622	0.0500	0.0828	0.5189	0.4811	0.8047	1.3307
2006	0.1301	0.0689	0.0611	0.0516	0.0849	0.5300	0.4700	0.8438	1.3880
2007	0.1286	0.0670	0.0616	0.0549	0.078	0.5207	0.4793	0.8907	1.2661
2008	0.1364	0.0719	0.0646	0.0615	0.0813	0.5267	0.4733	0.9523	1.2596
2009	0.1474	0.0683	0.0790	0.0609	0.0752	0.4638	0.5362	0.7701	0.9515
2010	0.1435	0.0734	0.0702	0.0638	0.0821	0.5110	0.4890	0.9093	1.1694
2011	0.1318	0.0672	0.0646	0.0615	0.0723	0.5096	0.4904	0.9520	1.1195
2012	0.1309	0.0638	0.0670	0.0609	0.0665	0.4877	0.5123	0.9085	0.9921
2013	0.1281	0.0585	0.0696	0.0556	0.0612	0.4566	0.5434	0.7980	0.8792
2014	0.1237	0.0556	0.0681	0.0491	0.0615	0.4492	0.5508	0.7208	0.9023
2015	0.1202	0.0520	0.0682	0.0481	0.0556	0.4325	0.5675	0.7046	0.8146
2016	0.1074	0.0449	0.0625	0.0395	0.0500	0.4184	0.5816	0.6321	0.8010
2017	0.0827	0.0317	0.0510	0.0375	0.0262	0.3829	0.6171	0.7353	0.5127
2018	0.0971	0.0387	0.0584	0.0362	0.0412	0.3989	0.6011	0.6195	0.7055
2019	0.0944	0.0373	0.0571	0.0356	0.0389	0.3951	0.6049	0.6240	0.6812

Notes: T is the Thiel coefficient; TER is the inter-regional Thiel coefficient; TRR is the intra-regional Thiel coefficient; TS is the Thiel coefficient of the South; TN is the Thiel coefficient of the North; TEC is the contribution of the inter-regional Thiel coefficient; TRC is the contribution of the intra-regional Thiel coefficient; TSC is the contribution of the Southern Thiel coefficient; TNC is the contribution of the Northern Thiel coefficient.

4.3. Evolution of Spatial Correlation Pattern

In order to explore the spatial correlation characteristics of the development level of open economy among municipal units in the YRDA, combined with Geoda software and spatial statistical analysis tools in ArcGIS, the global Moran'I (Table 7) of the development level of open economy among municipal units in the YRDA is calculated. Moran's I of the development level of the open economy in the YRDA from 2005 to 2019 is all greater than zero, which indicates that its distribution has a positive correlation. During the study period, the P and Z values passed the significance test, meaning that each municipal unit's spatial agglomeration effect was enhanced.

Table 7. The global Moran'I index of development level of open economy in YRDA from 2005 to 2019.

Year	Moran's I	*p* Value	Z Value	Year	Moran's I	*p* Value	Z Value
2005	0.28	0.02	3.30	2013	0.25	0.03	2.93
2006	0.29	0.02	3.43	2014	0.20	0.05	2.52
2007	0.28	0.01	3.40	2015	0.21	0.04	2.58
2008	0.25	0.03	3.07	2016	0.19	0.07	2.40
2009	0.31	0.01	3.64	2017	0.23	0.02	2.84
2010	0.21	0.04	2.77	2018	0.22	0.05	2.71
2011	0.25	0.04	2.95	2019	0.19	0.05	2.55
2012	0.25	0.03	2.93				

The global Moran's I verify the enhancement of the spatial distribution agglomeration of the development level of the open economy in the YRDA. Then the local autocorrelation model is introduced to test and concretely analyze the problems existing in the spatial distribution of the development of the open economy in the YRDA. The LISA figures (Figure 6) in 2005, 2010, 2015, and 2019 are drawn.

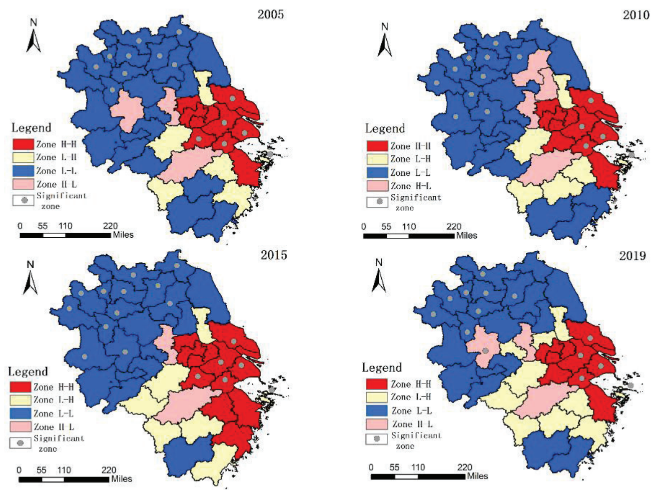

Figure 6. The LISA chart of the level of open economy in YRDA in 2005, 2010, 2015, and 2019.

As a whole, the local spatial autocorrelation of the development level of open economy in the YRDA is mainly dominated by the H-H and L-L districts, and spatial homogeneity is more prominent than spatial heterogeneity. In terms of spatial distribution, the spatial scope of the H-H area has an expanding trend and is mainly distributed in the middle and southeast of the Yangtze River Delta; the L-L region has evolved from agglomeration in the northwest of the YRDA to agglomeration in the west and north. The spatial distribution of the L-H and H-L regions is scattered, mainly in the south and middle. In space, the distribution pattern of "prominent in the middle, high in the south, low in the north, high in the east and low in the west" is formed.

4.4. Analysis of Influencing Factors

4.4.1. Model Selection

From the previous analysis, we know that the development level of the open economy in the YRDA has a certain spatial correlation, so we choose the SDM to analyze the influencing factors (Figure 7). Before the model selection, we conducted stationarity and multicollinearity tests on the collected panel data to avoid spurious regression. The results showed that the panel data was relatively stable. But we found that the variance inflation factors of two variables, GDP per capita (X1) and the post and telecommunications business volume (X9), were much larger than the critical value of 10, so they failed the test and were removed. Therefore, the remaining eight explanatory variables were selected as the influencing factors of the level of open economy development in the YRDA and used to construct a relevant analysis model. We take the logarithm of all indicators to eliminate the effect of heteroscedasticity. Then, we combine the three-step method proposed by Elhorst to select the specific form of the spatial panel measurement model [56].

First, the LM test is used to determine whether to reject the non-spatial model and accept the spatial lag model (SLM), the spatial error model (SEM) or the SDM. According to the *p*-value results of four statistics LM Spatial Lag, Robust LM Spatial Lag, LM Spatial Error and Robust LM Spatial Error that the null hypothesis that there is no SLM or SEM is rejected, so the Spatial econometric model should be chosen (Table 8). Secondly, the data are subject to the Hausman test to determine whether to select the fixed or random effect. The results show that the Hausman test rejects the null hypothesis at the significance level of 1%. Hence, the model using spatial fixed effects is more consistent with the model's estimation effect than random effects. In addition, the model can be controlled according to individual fixed effect, time fixed effect and double fixed effect, and time fixed effect is selected as the best model by comparing goodness of fit R^2. Finally, the SDM is constructed on this basis, and whether the SDM can be simplified to SLM or SEM is tested by Wald and LR statistics. The test results of Wald and LR both passed the significance test and rejected the original hypothesis, which indicates that SDM cannot be simplified to SLM and SEM. Therefore, the SDM is the most appropriate choice.

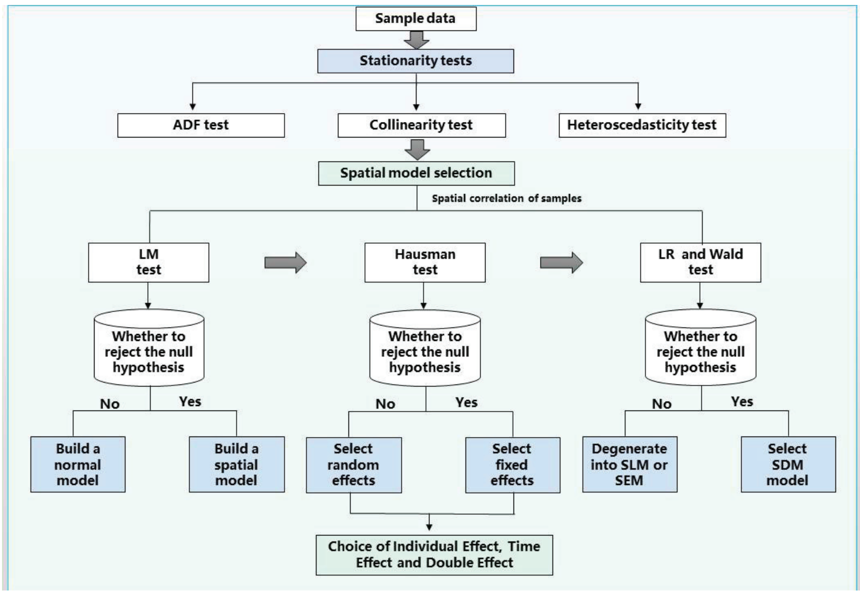

Figure 7. The flow chart of model selection.

Table 8. Spatial econometric model test results.

Test of Spatial Econometric Model		Statistics
LM Test	LM_Spatial error	61.199 ***
	Robust LM_Spatial error	17.747 ***
	LM_Spatial lag	53.203 ***
	Robust LM_Spatial lag	9.751 ***
Hausman Test		77.470 ***
LR Test	LR Test for SLM	105.290 **
	LR Test for SEM	90.180 ***
Wald Test	Wald Test for SLM	115.110 *
	Wald Test for SEM	101.100 ***

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

4.4.2. Analysis of Model Results

Before carrying out the spatial econometric model analysis, we first took on the ordinary panel model regression and compared the two regression results. It can be seen from Table 9 that the regression coefficients of the ordinary panel model and SDM of per capita financial expenditure (X2), human capital level (X6), freight volume (X8), and labor factor (X10) are all positive and passed the significance test, which indicates that these four factors have a significant positive impact on the development of the open economy in this region, but the lag coefficients are all negative, which indicates that after the addition of spatial factors, the improvement of these factors can facilitate the efficient development of the overall open economy in this region and the YRDA, but will restrain the progress of the development level of the open economy in the neighboring areas. The ordinary panel model regression coefficient, spatial Durbin model regression coefficient, and lag coefficient of per capita retail sales of social consumer goods (X5) are all positive and have passed the significance test, which indicates that the improvement of this factor has a significant positive impact on the overall development level of open economy of the YRDA. Meanwhile, the development of this region has spillover effects on the neighboring cities. The regression coefficient of the ordinary panel model of the proportion of the secondary and tertiary industries (X3) is significantly positive. In contrast, the regression and lag coefficient of the SDM does not pass the significance test, which indicates that without considering the spatial factors, there is a significant positive correlation between this factor and the development level of the open economy in the YRDA. The regression coefficient of the ordinary panel model of the urbanization rate (X4) is positive but insignificant. In contrast, the regression and lag coefficients of the SDM are significantly positive, which indicates that it cannot only promote the efficient development of the overall open economy in the YRDA to a certain extent but also has a significant positive spatial spillover effect on the adjacent areas. The regression coefficient of the ordinary panel model of the proportion of science and technology expenditure to financial expenditure (X7) is negative. The regression coefficient of SDM is positive but does not pass the significance test. The lag coefficient is significantly negative, which indicates that under the action of spatial factors, this factor will positively impact the development level of open regional economy. Still, it has a competitive relationship with the neighboring regions.

Table 9. The regression results of the ordinary panel model and spatial Durbin model.

Explanatory Variable	OLS		SDM		The Lagged Item Result		
	Coefficient	Standard Error	Coefficient	Standard Error	Variable	Coefficient	Standard Error
X2	0.1628 ***	0.0330	0.4119 ***	0.3277	W*X2	−0.2098 ***	0.0407
X3	1.0667 *	0.2183	−0.0884	0.1953	W*X3	0.1529	0.1721
X4	0.1134	0.0261	0.0707 ***	0.0212	W*X4	0.1448 ***	0.0246
X5	0.2115 **	0.0415	0.3043 ***	0.0376	W*X5	0.1458 ***	0.0405
X6	0.1325 ***	0.0200	0.0405 **	0.0173	W*X6	−0.0867 ***	0.0190
X7	−0.0704	0.0166	0.0090	0.0186	W*X7	−0.0396 **	0.0171
X8	0.0047	0.0196	0.0473 *	0.0184	W*X8	−0.0622 ***	0.0188
X10	0.1629 *	0.0184	0.1178 ***	0.0158	W*X10	−0.0492 ***	0.0178
ρ	——				0.1713 ***		
Log-likelihood	——				147.1855		
N	615				615		
R^2	0.8442				0.9425		

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

4.4.3. Robustness Test

In order to conduct a robustness evaluation on the above estimation results, the range attenuation weight matrix applied by Zhou [57] and Liu [58] is used to test the robustness. After Hausman, LR, LM, and Wald tests, the SDM is finally selected for estimating parameters. See Table 10 for the results. From the perspective of regression results, under the action of the range attenuation weight matrix, the proportion of the secondary and tertiary industries (X3) changed from negative to positive, and there were no fundamental changes in the significance of the other variables. By comparison, the analysis results based on the two kinds of weight matrices are the same, which indicates that the conclusion of the analysis part of influencing factors is robust and reliable.

Table 10. The regression results of the robustness test.

Explanatory Variable	SDM		The Lagged Item Result		
	Coefficient	**Standard Error**	**Variable**	**Coefficient**	**Standard Error**
X2	0.4167 ***	0.0332	W*X2	−0.2044 ***	0.0413
X3	0.1888	0.1959	W*X3	0.2228	0.1805
X4	0.0729 ***	0.0210	W*X4	0.1374 ***	0.0232
X5	0.2789 ***	0.0388	W*X5	0.1510 ***	0.0420
X6	0.0355 **	0.0175	W*X6	−0.0918 ***	0.0194
X7	0.0030	0.0188	W*X7	−0.0286 *	0.0173
X8	0.0410 **	0.0184	W*X8	−0.0539 ***	0.0187
X10	0.1290 ***	0.0160	W*X10	−0.0682 ***	0.0179
ρ			0.1939 ***		
Log-likelihood			149.8725		
N			615		
R^2			0.9431		

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

5. Discussion

Currently, China's economy has entered a double-cycle strategic model which takes the tremendous domestic cycle as the main body, coordinates the domestic and international double cycles, and plans new economic growth points [59]. The high-level development of an open economy must be based on the interaction between the domestic economy and the international market. It is necessary to adhere to and improve the basic economic system of socialism with Chinese characteristics, promote the modernization of the national governance system and governance capacity, highlight the vital role of the government in promoting the efficient development of an open economy, create a long-term, stable, predictable and high-quality environment under the rule of law, build a high-standard market system, and encourage all kinds of market entities to release economic vitality to cope with the more complex and severe global industrial chain and foreign trade environment, form a new model of innovation-driven open economy development, and promote and lead the sustainable development of the open global economy [60]. So, what can we learn from this study?

5.1. It Is Necessary to Promote Regional Coordinated Development with the New Development Pattern of Domestic and International "Double Cycles"

Coordinated development is an essential index for reflecting high-quality development [61]. Suppose the development gap between regions is too broad. In that case, a scientific and efficient division of labor and cooperation between relatively developed and underdeveloped areas will not be formed, which will hinder the construction of an open economy, let alone the efficient development of an open economy [62]. From the results of the spatio-temporal analysis in part 4, it can be seen that the development level of the open economy of each city in the YRDA shows a fluctuating and rising trend over time, but the absolute and relative differences are enlarged, and the development level is uneven. In space, it shows a pattern of "prominent in the middle, high in the south, low in the north, high in the east and low in the west", and the regional differences among the subsystems also show a trend of increasing at first and then decreasing. The new development pattern can promote the circulation of various resource elements at home and abroad by optimizing the market layout to promote the region's coordinated development and the open economy's high-quality development [63].

Under the "Double cycle" pattern, as an essential hub of the double cycle system, the YRDA can achieve internally balanced and coordinated development better and faster through industrial chain transfer, upgrading, and reconstruction [64]. In addition, the degree and quality of coordinated development among different cities in the YRDA are also the key factors that determine the smoothness of the overall economic cycle under the new development pattern of the "Double cycle". It is not only an essential basis for accelerating the high-level development of an open economy but also an important guarantee for social harmony, political stability, and sustainable economic development to promote coordinated regional development. On the one hand, we can encourage the logical flow and efficient agglomeration of various elements through the regional coordinated development strategy to help smooth the domestic cycle, and control the regional development gap within a reasonable range under the condition of taking the domestic cycle as the main body, give full play to the competitive advantages of different cities in the YDRA and form a high-coupling industrial chain network with the mutual division of labor. On the other hand, it is necessary to deepen foreign economic ties, make good use of two markets and two kinds of resources, promote the establishment of an Omni-directional, wide-range, and multi-level open financial system, and promote the benign interaction of domestic and international double cycles in the YRDA to move forward the middle and high end of the global value chain [65].

5.2. Government Services Provide Essential Support for the Development of the Open Economy

In China's economic system reform, the relationship between the government and the market has always been an inevitable and essential issue [66]. With the deepening of reform and opening up, our government has constantly explored the orientation of its functions in practice, deepened the understanding of its functions, and continuously adjusted the focus of its functions [67]. In constructing an open economy, the government should focus on creating an excellent institutional environment and providing policy support for the high-level development of the open economy, providing public goods and services, and establishing an economic regulation and control system compatible with the development of the open economy [68]. Since the reform and opening up, the open economy in the YRDA has made remarkable achievements [69]. In 2020, the total foreign trade of the YRDA was USD 1.63938 trillion, and the amount of foreign investment utilized was USD 82.329 billion, accounting for 35.8% and 59% of the country's total, respectively. It plays an essential leading role in driving the rapid development of China's open economy. These achievements cannot be achieved without a series of supporting policies to encourage the development of an open economy. This conclusion is also confirmed by our study, as can be seen from the analysis results, government factors such as per capita financial expenditure, per capita retail sales of social consumer goods, the proportion of science and technology expenditure in financial spending, and the development of urbanization have a significant impact on the development level of the open economy in the YRDA, which to a certain extent reflects that it is crucial to formulate targeted and comprehensive supporting policies to encourage the development of an open economy. Therefore, it is necessary to constantly improve the social security system and residents' income growth mechanism, establish a consumer rights protection system and a class action system, improve the financial redistribution adjustment mechanism, effectively expand domestic demand and promote domestic circular development; improve the functional design of government public services, innovate the supply mechanism of essential public services, improve the efficiency and quality of public services, and create a good market environment for the construction of an open economy [70]; optimize the mechanism for cultivating, introducing and retaining talents, provide talent guarantee for the development of open economy, improve financial support measures, and support foreign-funded enterprises to explore the international market; discount financing loans and achieve technology transformation and renovation.

5.3. An Innovation-Driven Engine also Needs to Be Built for the High-Level Development of the Open Economy

As China has entered a new stage of high-quality development, the open economy of the YRDA should not only maintain the forefront of the country but shall also be transformed from quantity to quality faster. Innovation is regarded as the key driving force to lead the development and the critical support to promote the efficient development of an open economy [71], because growth is driven by knowledge accumulation, technological progress, and the improvement of labor quality. Knowledge innovation, technological innovation, and management innovation can effectively enhance the core competitiveness of enterprises and then stimulate the quality and potential of development of the open economy. Although the YRDA is the region with the most economic vitality, the highest level of openness, and the most robust innovation ability in China, internationally, due to the rising global industrial technical barriers and the developed countries' control or suppression of technology export to China, the stock of technology that can be introduced into China is becoming less and less, especially the critical core technology and "Containment " technology have become the trump card created by developed countries to suppress China. Due to technological bottleneck, China's scientific and technical foundation is relatively weak [72]. There is a relatively high import dependence on core key technologies and components, which may also lead to the low development level of the potential of the open economy subsystem of development of open economy in the YRDA and be the reason that the proportion of science and technology expenditure in financial expenditure has not played a full role in promoting it. Therefore, it is necessary to build a new open economic system that can promote innovation-driven development [73]; take scientific and technological innovation as the center, realize power transformation in the process of improving the quality and efficiency of the development of an open economy, and strengthen the combination of mobile Internet, cloud computing technology, big data, Internet of Things and international trade, to promote the development of the open economy by forming a new driving force of innovation; pay attention to the cultivation of innovative talents, improve the investment level of education and human capital, through the protection of intellectual property rights, maintain the interests of individual innovation and organizational innovation at the institutional and legal status, and finally realize the systematic innovation of economy and society.

6. Conclusions and Deficiencies

Under the guidance of the new development pattern of the domestic and international "Double cycle", the development of the open economy is facing both good development opportunities and significant challenges. YRDA can only promote the development of the open economy better and faster by defining its own position and recognizing its shortcomings in future development. Based on analyzing the development mechanism of China's open economy at the present stage, this paper reveals its spatio-temporal pattern and its existing problems by measuring the development level of the open economy in the YRDA and then uses the SDM to analyze its influencing factors to find ways to improve the quality of development given the existing problems to achieve its sustainable and healthy development. The study found that: (1) From 2005 to 2019, the development level and differences of open economy in the YRDA showed an upward trend, and the trend of differences among subsystems was complex. (2) From the spatial point of view, the development level of each region shows a spatial distribution pattern of "prominent in the middle, high in the south, low in the north, high in the east and low in the west". The regional difference shows a trend of increasing at first and then decreasing. The effect of spatial agglomeration is constantly strengthening, and spatial homogeneity is more prominent than spatial heterogeneity. (3) The per capita financial expenditure, labor factor, urbanization rate, per capita retail sales of social consumer goods, human capital level, and freight volume play a prominent role in improving the development level of the open economy in this region. Urbanization rate and per capita retail sales of social consumer goods have a significant positive impact on the development of the YRDA and neighboring regions. The human capital level, the proportion of science and technology expenditure in financial expenditure, freight volume, and labor factors are the factors that hinder the development of the open economy in neighboring regions and regions as a whole. (4) In the stage of high-quality development, the YRDA should promote regional coordinated development with the new development pattern of domestic and international "Double cycle", improve the quality of government services to provide a guarantee for high-level development and create an innovation-driven engine to promote open economy to high-quality development.

By studying the open economy's development level in the YRDA and its influencing factors, this paper preliminarily discusses the essential characteristics of its development. However, it is still also necessary to further improve the relevant mechanism and theoretical analysis of the transformation of the open economy from scale and speed dominance to quality and efficiency dominance. Meanwhile, since there is a limitation of data acquisition and reserve, the data of the research sample can only be collected until 2019, but the follow-up research can expand it to 2022 to further explore the relevant impact of the COVID-19 on China's open economy development. In addition, this paper discusses the role of the new development pattern of the domestic and international "Double cycle" in promoting the coordinated development of the open economy in the YRDA. On this basis, in the future, we can carry out an in-depth study on the high-quality development of the open economy from the perspective of the new development pattern of the double cycle to enrich the relevant study results.

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Article

Environmental Regulation and Green Technology Diffusion: A Case Study of Yangtze River Delta, China

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Abstract: As an important driver of green technology innovation, the impact of environmental regulation on the diffusion of green technology remains controversial. Taking China's Yangtze River Delta (YRD) urban agglomeration, as an example, and using green patents transfer to measure green technology diffusion, this paper analyzes the effect of environmental regulation on green technology diffusion by revealing the temporal and spatial characteristics of green technology diffusion in the YRD. The results show that: (1) Green technology transfer activities in the YRD mainly take place in Shanghai, Hangzhou, Nanjing, Suzhou, and other cities. (2) Green building technology is the most demanded technology in the green technology transfer market in the YRD. (3) The direction of green technology diffusion in the YRD has changed significantly over time. In the early stage, green technologies mainly flowed to developed cities such as Shanghai, Suzhou, and Nanjing. However, in the later stage, green technologies mainly flowed from developed cities such as Shanghai, Suzhou, and Nanjing to cities with lower economic development levels (mostly located in Anhui Province). (4) The consistency of environmental regulation among cities plays an important role in promoting green technology transfer within the YRD, which is precisely what the YRD ecological green integrated development strategy emphasizes, breaking the administrative barriers between cities in the YRD and accelerating the flow of green technology between cities.

Keywords: environmental regulation; green technology diffusion; Yangtze River Delta

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1. Introduction

In the face of problems such as global climate change, deterioration of the ecological environment system, and resource and environmental stress, sustainable development supported by responsible innovation or green technology innovation has become a global economic development strategy [1–3]. However, green technology innovation activities or the applicants for green patents are highly concentrated in a few developed countries (the United States, Japan, Germany, etc.) and even in a few large multinational companies. The distribution of countries in green patent cooperation treaty (PCT) applications, released by the World Intellectual Property Organization (WIPO) in 2019, showed that the first countries to apply for green energy patents accounted for more than 76% of the total global green energy patent applications in 2019 [4]. Therefore, the collaborative development and sharing of green technologies among countries, regions, cities, and enterprises is considered as a key measure to deal with global climate change and reduce environmental pollution and ecological damage [5,6]. As shown in in the report *Innovation and Diffusion of Green Technologies: The Role of Intellectual Property and Other Enabling Factors*, launched by the WIPO during a side event at UNFCCC's Bonn Climate Change Conference in June 2015, due to several market failures and other factors, the innovation and diffusion of environmental technologies pose particular problems that require a range of policy interventions. A range of policy interventions are needed to accelerate the process of green technology transfer from developed to developing countries, from developed to developing regions, and from large multinational corporations to SMEs.

From the "Beijing Declaration" to the construction of "two-oriented society", and the ecological civilization, green development, and construction of "beautiful China", China has become a great contributor and leader of global sustainable development, which can be verified by the rapidly growing number of green PCT applications in China [2]. However, the distribution of green technologies within China is extremely uneven, with a high concentration in a few cities along the eastern coast. Based on the above background, it has become a national strategic decision to build a market-oriented green technology innovation system that accelerates the process of green technology diffusion among regions and cities. In 2017, in order to promote the diffusion of scientific and technological achievements, the State Council of China issued the "National Technology Transfer System Construction Plan". In 2019, China's National Development and Reform Commission and Ministry of Science and Technology jointly issued the "Guiding Opinions on Building a Market-Oriented Green Technology Innovation System". However, due to institutional obstacles, especially the differences in environmental regulations between regions or cities, there are still many challenges in the free flow of green technology between regions or cities.

The relationship between environmental regulation and green technology diffusion is a central topic in environmental economics, innovation economics, and science and technology management. Unlike the clear positive relationship between environmental regulation and green technology innovation, there is no consensus in the academic community on the impact of environmental regulation on green technology diffusion. As highlighted by technology gap theory, some scholars believe that regions with strong environmental regulations can stimulate the flow of green technologies from regions with weak environmental regulations to them [7]. Other scholars argue that inter-regional environmental regulation intensity differences are similar to those emphasized by multidimensional proximity theory. The more similar the environmental regulation intensity between regions is, the stronger the green technology flows between them [8]. The reason for this contradiction may be that different scholars have adopted different methods in measuring the intensity of environmental regulation and the flow of green technology, though it may also be due to the different analysis cases adopted by scholars. Just as research into enterprise green technology innovation has found, due to differences in scale, knowledge base, etc., enterprises also have great differences in the degree of adopting green technology in response to government environmental regulations [7–10].

In response to the above debate, this paper takes the Yangtze River Delta of China as a case area to explore the relationship between environmental regulation and the diffusion of green technologies. The aim of this paper is to verify the influence mechanism of the consistency of intercity environmental regulations on the flow of intercity green technology, based on revealing the spatial–temporal characteristics of intercity green technology flow in the Yangtze River Delta. The contributions of this paper are mainly two aspects. One is to measure the intercity green technology flow through intercity green patent transfer, the other is to further verify the importance of environmental regulation on green technology diffusion.

The rest of the paper is organized as follows: Section 2 reviews the relevant literature, Section 3 introduces the data sources and methods, Section 4 presents the green technology diffusion pattern and data simulation results in the YRD, and Section 5 gives the conclusions of the paper.

2. Theoretical Framework

Since the 1960s, as the contradiction between economic growth and environmental degradation has become increasingly prominent, research on green technology innovation has gradually emerged. Similar to general technology diffusion, green technology diffusion can maximize the application value of eco-innovation R&D results. At the same time, green innovation diffusion also has practical significance for improving the environmental benefits of society, practicing national ecological strategies, and achieving sustainable development. In other words, the diffusion of green technology is even more important than the green technology itself.

A number of in-depth studies on the influencing factors of green technology diffusion with different perspectives have been conducted by scholars from different fields, including innovation theory, stakeholder theory, the resource-based view, etc. In general, the factors influencing green technology diffusion are green technology attributes (supply push), innovator capabilities, adopter capabilities (demand pull), and environmental regulations (regulatory push/pull) [11]. First of all, the attributes of green technologies can significantly impact the speed of their adoption, and, therefore, complex green technologies may spread more slowly. Secondly, innovators' capabilities also play an essential role in the diffusion of technology. Firms are usually more efficient in technology diffusion than universities, research institutions, or individuals [12]. Third, the adopters' resources and capabilities also have an effect on the diffusion of green technology, and weak production and manufacturing capabilities can prevent firms or other institutions from adopting green technologies [13].

As a driver of green innovation diffusion, environmental regulation has received the most attention. Green innovation is characterized by a double externality, implying that adopters of green technologies need to internalize the cost of reducing environmental hazards, which makes environmental regulation strongly influence the diffusion process of green innovation [14]. There are three major perspectives on the relationship between environmental regulations and green technology diffusion. Some scholars argue that strict environmental regulations at the inflow site inhibit the diffusion of green technologies, which is based on the theory of neoclassical economics that environmental regulations such as energy policies and taxes increase the cost burden of firms, stimulating the green effect paradox and inhibiting firms' incentives to adopt green technologies [15]. In addition, green technologies are usually initially developed, which means, compared with other investments, they are riskier, more uncertain, and do not yield the same corresponding benefits in the short term as existing non-green technologies [16]. At the same time, environmental standards and regulations make companies less motivated to make an effort regarding green innovation. When faced with meeting environmental standards or regulatory requirements, companies have no motivation to develop or adopt new green technologies to reduce pollution [17].

It has also been argued that environmental regulations can promote the diffusion of green technology. First, well-designed environmental regulations can stimulate the innovation compensation effect, which can positively affect green technology diffusion by compensating firms for the increased compliance costs of developing and adopting green technologies [18]; this is the famous Porter hypothesis, which has been verified by many subsequent studies [19,20]. At the same time, market-based instruments such as innovation subsidies and permits can provide a cost-effective response to environmental problems. Based on characteristics, firms can choose the most efficient way to improve their environmental performance [9]. Moreover, strict environmental regulations provide new technological opportunities and create a huge demand for green innovation. For example, some studies have found that top researchers prefer to develop environment-related offshore innovation activities in host countries with strict environmental regulation policies, as such stringent environmental regulations motivate them to localize their green innovation activities [7].

Contrary to the above two perspectives, other scholars argue that the stringency of environmental regulations does not affect the flow of green technology. Similar environment regulations between the inflowing country and the outflowing region will increase the number of green technology transfers. Dechesleprêtre analyzed data on vehicle emission standards and nonresident patents for 72 countries from 1992–2007 and found that when the regulatory standards in the inflowing region are more similar to those in the inventing country, more green technologies would flow into those countries [8].

All the above studies focus on micro- (institutions, companies) or macrolevel (countries), and microlevel studies often collect data by distributing questionnaires to companies, using the adoption rate of green energy efficient technologies [21] or the adoption of green energy technologies [8,9] as a measure of green technology flows. Macrolevel studies, on the other hand, often use cross-border patent application data as a measure of green technology flows [22]. Studies on the spatial diffusion of green technologies at the city scale are not common. This paper uses the number of green patent transfers to measure urban green technology flows. Since technology transfer is the key to innovation diffusion [23], a multilevel perspective of technology transfer studies is becoming one of the popular themes.

Patent data have higher reliability and broader coverage than questionnaire data. In addition, with the development of networks, the diffusion of green technology has shown complex network characteristics [24]. It has become a future research trend to adopt complex network theory to analyze green technology diffusion [25]. China has the largest green technology market, and, notably, the YRD is the pioneering region of green technology in China. Therefore, this paper analyzes the spatial and temporal patterns of green technology transfer in the YRD using social network analysis, which analyzes the impact of environmental regulation on green technology transfer, based on triangular green technology transfer data, and uses Quadratic Assignment Procedure (QAP) regression. The results help to clarify the following research questions:

How does the environmental regulation affect the inter-regional diffusion of green technologies in the context of regional leading markets? In what spatial pattern is the diffusion process of green technologies organized?

3. Data and Methods

3.1. Study Area

The YRD region is the intersection of the Yangtze River Economic Belt and the eastern coastal development belt, which includes Jiangsu, Zhejiang, and Anhui provinces and Shanghai, with a total of 41 cities. It is the most representative urban agglomeration in China and the top priority for China's economic development. In 2020, the YRD region generated USD 24.47 trillion in regional GDP, accounting for 24.1% of China's GDP, though the region covers only 3.6% of China's land area. Meanwhile, ecological green development has been the leading direction of economic development in the YRD region. In December 2019, the State Council of China issued the "Outline of the YRD Regional Integrated Development Plan", which explicitly proposes to strengthen the construction of a collaborative innovation industry system and strengthen the common protection and joint management of the ecological environment. Innovation-driven and green development have become the leading directions of economic development in the YRD region. In 2022, Jiangsu, Zhejiang, and Shanghai jointly issued "Several Policy Measures on Further Supporting the High-Quality Development of the YRD Ecological and Green Integrated Development Demonstration Zone", to further promote high-quality development of the YRD ecological and green integration. Under this background, remarkable achievements have been made in environmental governance, and technology transfer activities are very active in the Yangtze River Delta region, which makes the YRD region a pioneer of China's green technology. In 2020, 4868 green patents were intercity-transferred in the YRD region, accounting for 24.5% of the national total. Nationwide, green patents were transferred with the participation of cities in the YRD, accounting for 65.3% of the total.

3.2. Data Sources and Processing

Green patents are direct evidence of innovation-driven sustainable development, and its transfer reflects the flow and sharing of green innovation knowledge between regions. Meanwhile, patent transfer has a specific commercial value and may about to be used for commercial purposes. Patent transfer can also analyze the direction and spatial scope of innovation diffusion from the transferor to the transferee. Therefore, this paper uses green patent transfer to measure green technology flow. Firstly, the data of Chinese patent transfer in 2010, 2015, and 2020 were retrieved from the Patent Information Service Platform of Intellectual Property Press (http://search.cnipr.com/, accessed on 13 January 2022), containing information such as patent application number, main classification number, registration effective date, rights holder before change, rights holder after change, address of rights holder before change, and address of rights holder after change. Secondly, the green patent identification system was constructed by the IPC patent classification number (including clean energy technology, greenhouse gas treatment technology, green transportation technology, green building technology, environmental management technology, and green water technology) [26], and the green patent transfer data are selected from the complete sample data. Finally, based on the information of "the address of the rights holder before the change" and "the address of the rights holder after the change," the cities of the rights holder before the transfer of green patents and the cities of the rights holder after the transfer are identified, and the green patent transfer data related to 41 cities in the YRD are screened. The processed information of cities before and after patent transfer is used as the basic information of directional relationship nodes, and ArcGIS is used for visualization.

3.3. Methods

3.3.1. Network Construction

With cities as nodes and the number of green patents transferred between cities as edges, the weighted directed green technology diffusion network in the YRD is constructed. The green technology diffusion network mainly portrays the intercity technology transfer relationship. All nodes in the network are cities within the YRD, and its network boundary is its administrative boundary.

3.3.2. Variables Selection

The explained variable of this paper is the number of green patents that transfer from one city to another. The central explanatory variable in this paper is the intensity of environmental regulation. The established literature quantifies environmental regulation in four main ways. One is to measure environmental regulation in terms of environmental governance expenditures, such as government incentives to invest in policies [27]. The second is to measure environmental regulation in terms of pollutant emission levels or treatment levels, such as pollutant emissions or pollutant treatment rates [28]. The third is the establishment of a comprehensive evaluation system of environmental regulation to create comprehensive indicators in three dimensions: input, process, and outcome [29]. The last method is to use alternative indicators to measure environmental regulation, which is to prevent environmental regulation from being too complex [30]. Comparing the above four methods, the most reasonable method is to construct a comprehensive evaluation system of environmental regulation. However, it is difficult to apply this to city-scale studies due to data availability. In addition, it is difficult to obtain data on pollutant emission reduction expenditures at the urban scale level in China. However, official statistics on pollutant emission levels are available. Based on previous studies [28], three indicators are used in this paper, namely general industrial solid waste comprehensive utilization rate, domestic sewage treatment rate, and domestic waste harmless treatment rate, and entropy value method is used to construct the urban environmental regulation intensity index.

The study of drivers in green technology diffusion in enterprises provides a reference for selecting the control variables of intercity green technology diffusion influence factors in this paper [31]. Knowledge base theory suggests that the knowledge base of a subject largely determines its ability to acquire external knowledge [32]. In terms of green technology diffusion in enterprises, enterprises' existing green technology innovation capacity is often used as the basic variable, which determines their ability to absorb and supply green technology. Meanwhile, technology gap theory suggests that technology gaps can induce technology transfer, such as the technology transfer from developed to developing countries [33]. Previous studies have also shown that technology gap is one of the drivers of intercity technology diffusion in China.

Environmental economics theory suggests that firm's attribute plays an important role in green technology diffusion. In intercity green technology diffusion, there will be differences in green technology diffusion due to cities' different essential characteristics. Economic development drives the transformation and upgrading of urban industrial structure, which determines what type of green technology output is high and what type of green technology is in high demand in cities. Usually, cities with mainly dominant secondary industries tend to have a higher demand for green technologies in the production and emission stages than cities with mainly dominant primary or tertiary sectors.

The government's scientific and technological support are equally important in the diffusion of green technologies. The local government's support for scientific research and education can, on the one hand, play a guiding demonstration role and, on the other hand, can reduce the pressure and risk of the enterprises' initial investment. Therefore, government support in scientific research and education can stimulate intercity green technology transfer. Human capital is key to developing green innovation capacity in cities, and it can help to improve their green innovation capacity. Meanwhile, the higher the level of human capital is, the higher the feasibility of green technology and the lower the upfront risk that enterprises take to adopt green technology.

In this paper, five control variables are constructed, which are selected from economic development level, industrial structure, human capital, knowledge base, and government support. Economic development level is measured by GDP; the industrial structure is measured by the proportion of tertiary industry to GDP; human capital is measured by the number of full-time teachers in general higher education institutions; the knowledge base is measured by the number of green technology applications in cities; and government support is measured by the scale of R&D funding investment. All of the above data are derived from the China City Statistical Yearbook.

3.3.3. Quadratic Assignment Procedure

In this paper, the impact of environmental regulation on green technology diffusion in the YRD is analyzed through the QAP regression method, which examines the relationship between the matrix of dependent variables and the matrix of multiple independent variables. The method takes relational data as the research object and has no strict requirements for independence between variables, and the regression results are more robust than conventional methods [34]. The QAP model was developed as follows.

$$R = (ERR, IND, GDP, HUM, SRE, KNO) \tag{1}$$

where R is the dependent variable, which represents the green patent transfer matrix, ERR, IND, GDP, HUM, SRE, and KNO are independent variables, which represent the environmental regulation, industrial structure, economic linkage, human capital, government support, and knowledge base, respectively.

3.3.4. Gravity Model-Based City Correlation Measurement

The green patent transfer network constructed in this paper is a directed network, i.e., the green technology diffusion between cities is differentiated and directional. Likewise, the contributions of the two cities to the spatial correlation of influencing factors such as environmental regulation and economic linkages between them are also different. It has been generally revealed that green technology innovation between cities or regions has significant spatial correlation characteristics, and the intensity of environmental regulation between cities or regions also shows similar characteristics of spatial proximity. Therefore, this paper uses a modified gravity model considering the geographic distance between cities to measure the spatial correlation degree of each factor of green technology diffusion between cities in the YRD, as in Equation (2).

$$\eta_{ij}^{k} = v_{ij}\frac{X_i^k X_j^k}{Geo_{ij}}, v_{ij} = \frac{X_i^k}{X_i^k + X_j^k} \quad (2)$$

where η_{ij} denotes the spatial correlation degree of city i to city j on the k factor, X denotes the driving factor of each city, Geo_{ij} denotes the geographic distance between two cities, v_{ij} is the modified empirical constant, and X contains the six driving factors selected above. Meanwhile, due to the different units of measurement of different matrices, this paper also adopts the Z-value method to standardize each influence factor network matrix, so that the mean value of each driver matrix is 0 and the standard deviation is 1. The specific variables and measurement methods are shown in Table 1.

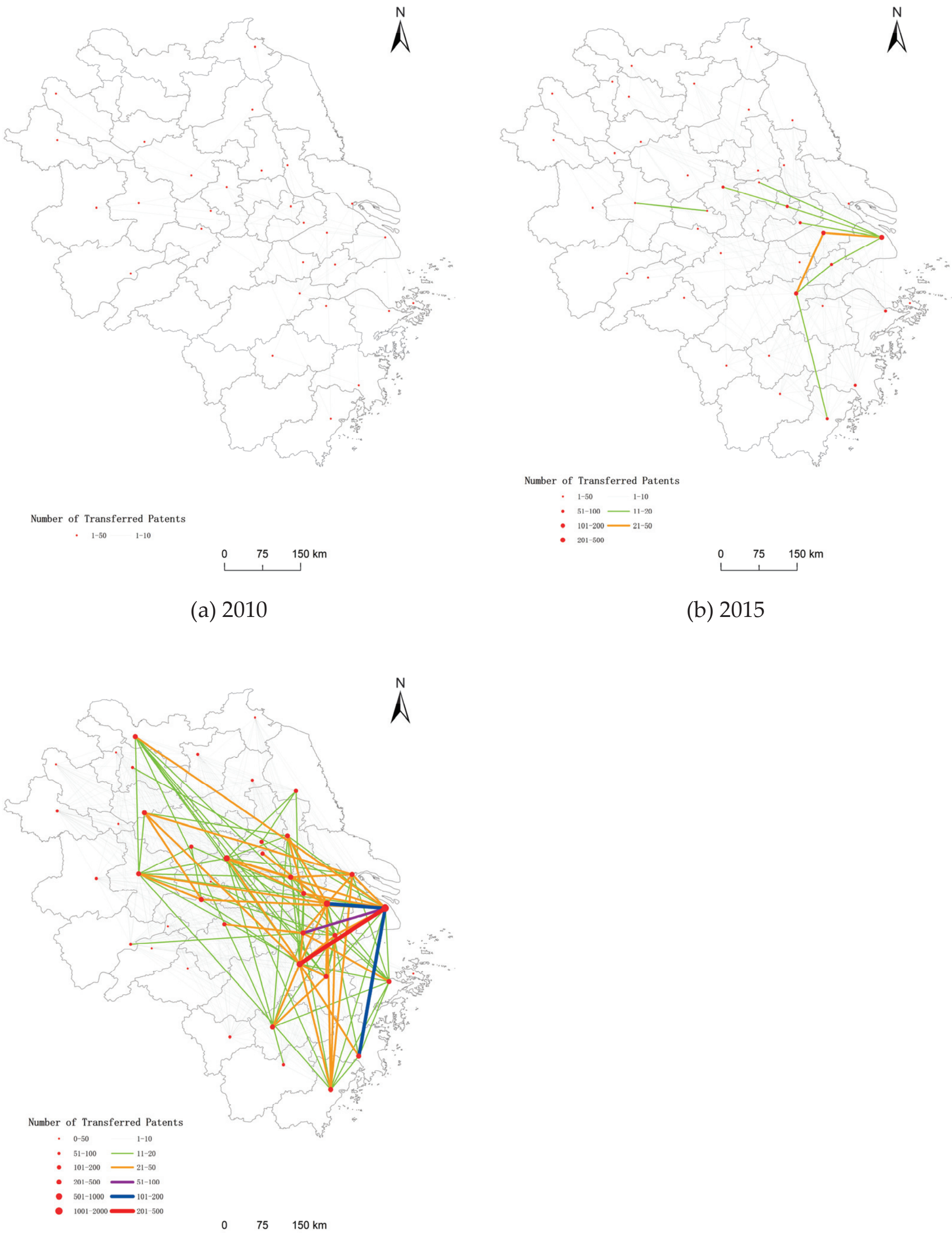
Table 1. Variable descriptions.

Variable Name	Variable Symbols	Measurement
Spatial relevance of environmental regulation	$ERR_{i \to j}$	The three indicators of general industrial solid waste comprehensive utilization rate, domestic sewage treatment rate, and domestic garbage harmless treatment rate are selected to construct the urban environmental regulation intensity index using the entropy value method, and the spatial correlation from city i to city j in environmental regulation is measured using Equation (2).
Economic linkage spatial relevance	$GDP_{i \to j}$	Use city GDP to represent the level of economic development of cities and use Equation (2) to measure the spatial correlation from city i to city j in terms of economic development.
Spatial correlation of industrial structure	$IND_{i \to j}$	Use the ratio of tertiary industry output value of cities to represent the industrial structure of cities, and use Equation (2) to measure the spatial correlation from city i to city j in terms of industrial structure.
Spatial correlation of human capital	$HUM_{i \to j}$	The number of university faculty in the city is used to represent the human capital of the city, and the spatial correlation from city i on city j in terms of human capital is measured using Equation (2).
Government support spatial relevance	$SRE_{i \to j}$	Using the scale of city R&D expenditure to represent the city government financial support, and using Equation (2) to measure the spatial correlation from city i to city j, in terms of government support.
Knowledge base spatial relevance	$KNO_{i \to j}$	Use the city green patent applications to represent the city knowledge base, and use Equation (2) to measure the spatial correlation from city i to city j in the knowledge base.

4. Results

4.1. Mapping the the Diffusion of Green Technology in YRD

From 2010 to 2020, the number of green patents transferred in the YRD region increased rapidly, from 101 in 2010 to 4868 in 2020. The number of cities participating in green technology transfer in the area also increased from 28 to 41. Over the past 10 years, the pattern of green technology transfer in the YRD has developed from point-like scattering to forming a network in the east and spreading to the west and north. The flow of patents has shifted from clustering in the east to spreading from the east to the central and western regions (Figure 1 and Table 2).



(a) 2010

(b) 2015

(c) 2020

Figure 1. Green technology diffusion in YRD from 2010 to 2020. Data source: Patent Information Service Platform of Intellectual Property Press. Available online: http://search.cnipr.com/pages!advSearch.action (accessed on 13 January 2022).

Table 2. Top 10 intercity links of green technology transfer in YRD.

Order	2010			2015			2020		
	Transfer Out	Transfer In	Number	Transfer Out	Transfer In	Number	Transfer Out	Transfer In	Number
1	Suzhou	Shanghai	10	Suzhou	Shanghai	34	Shanghai	Hangzhou	209
2	Shanghai	Suzhou	10	Hangzhou	Suzhou	33	Shanghai	Taizhou	198
3	Changzhou	Wuxi	7	Shanghai	Suzhou	22	Shanghai	Suzhou	130
4	Shanghai	Jiaxing City	5	Zhenjiang	Shanghai	15	Shanghai	Huzhou City	51
5	Jinhua	Taizhou	5	Changzhou	Shanghai	14	Nanjing	Changzhou	50
6	Ningbo	Shanghai	4	Wuxi	Shanghai	13	Shanghai	Jiaxing City	50
7	Millipore	Ma'anshan City	4	Changzhou	Nanjing	13	Nanjing	Suzhou	49
8	Wenzhou	Suzhou	3	Hangzhou	Jiaxing City	13	Suzhou	Shanghai	48
9	Taizhou City	Suzhou	3	Ma'anshan City	Hefei	13	Hangzhou	Jiaxing City	47
10	Shanghai	Hangzhou	3	Wenzhou	Hangzhou	13	Hangzhou	Huzhou City	46

Data source: Patent Information Service Platform of Intellectual Property Press. Available online: http://search.cnipr.com/pages!advSearch.action (accessed on 13 January 2022).

In 2010, the volume of green technology transfer and the number of participating cities in the YRD region were 101 and 28, respectively, with 19 cities transferring out of green technology, 18 cities transferring into green technology, and 16 cities absorbing and spreading out green technology. In 2015, the volume of green technology transfer and the number of participating cities in the YRD region were 711 and 40, respectively, with 38 cities transferring out of green technology, 39 cities transferring into green technology, and 37 cities absorbing green technology as well as spreading it outward. In 2020, the number of green technology transfers soared to 4868, and all 41 cities in the YRD region participated in green technology transfers.

In terms of green technology transfer volume, Shanghai, Suzhou, Hangzhou, Nanjing, and Wuxi occupied the top five positions in 2010, with Shanghai ranking first with 39 green patents transferred (22 transferred out and 12 transferred in); Suzhou ranked second with 29 green patents transferred (10 transferred out and 19 transferred in); and Hangzhou ranked third with 20 green patents transferred (12 transferred out and 8 transferred in). In 2015, the top 10 positions were occupied by Shanghai and cities in Zhejiang and Jiangsu provinces. Shanghai ranked first, with 207 transferred green patents (94 transferred out and 113 transferred in); Suzhou ranked second with 150 transferred green patents (71 transferred out and 79 transferred in); and Hangzhou ranked third with 140 transferred green patents (92 transferred out and 48 transferred in). In 2020, 9 of the top 10 positions were taken by cities in Shanghai, Zhejiang, and Jiangsu. Shanghai ranked first, with 1157 transferred green patents (865 transferred out and 292 transferred in); Hangzhou overtook Suzhou and ranked second with 816 transferred green patents (447 transferred out and 369 transferred in); Suzhou ranked third with 796 transferred green patents (341 transferred out and 455 transferred in); and Hefei, in Anhui province, ranked first with 392 transferred green patents (270 transferred out and 122 transferred in). In 2010 and 2015, Shanghai, Hangzhou, and Suzhou occupied the core position of intercity green technology transfer in the YRD, with the volume of green technology transfer in these three cities accounting for more than 70% of the total intercity green technology transfer in the YRD. In 2020, Shanghai became the sole core of the network, accounting for 23.8% of the total green technology transfer volume in the YRD.

In terms of intercity green technology transfer relationship, in 2010, the strength of innovation linkage between cities was generally weak, and the strongest linkage was between Shanghai and Suzhou, with 10 of the 22 green patents transferred from Shanghai being transferred to Suzhou, and all 10 green patents transferred from Suzhou were transferred to Shanghai. This was followed by Changzhou and Wuxi, with 7 of the 10 green patents transferred from Changzhou being transferred to Wuxi. In 2015, Suzhou had a strong relationship with Shanghai and Hangzhou. Overall, 34 of the 71 green patents transferred from Suzhou were transferred to Shanghai, 33 of the 92 green patents transferred from Hangzhou were transferred to Suzhou, and 22 of the 94 green patents transferred from Shanghai were transferred to Suzhou. In addition, five pairs of cities, in the top 10 intercity links of green technology transfer in the YRD region, are cities in Shanghai and Jiangsu provinces, indicating that the links between Shanghai and Jiangsu Province in the YRD region are closer, and the green ecological integration of the YRD is yet to be further developed. In 2020, 209 of the 865 green patents transferred from Shanghai were transferred to Hangzhou, 198 were transferred to Taizhou, and 130 were transferred to Suzhou, which is also in the top three intercity links of green technology transfer in the YRD region. In addition, four pairs of cities, in the top 10 intercity links in the YRD region, are cities in Shanghai and Zhejiang Province, and two pairs are cities in Shanghai and Jiangsu Province, indicating that Shanghai is still the core of green technology transfer in the YRD region. However, compared with 2015, the relationship between Shanghai and Zhejiang Province is stronger. The closeness with Jiangsu Province has slightly decreased, and the green ecological integration in the YRD still needs further development.

In terms of spatial distribution, in 2010, the amount of intraregional green technology transfer in the YRD was small, and the network was sparse. In 2015, firstly, the network of green technology transfer in the eastern part of the YRD began to form a network. Secondly, the dominant position of YRD intraregional green technology transfer was occupied by Shanghai, Suzhou, and Hangzhou, and among 209 pairs of intraregional green technology transfer relationships, 86 pairs involved three cities, namely Shanghai, Suzhou, and Hangzhou. In addition, intraregional green technology transfer at this stage mostly showed clustering to the east in terms of direction. By 2020, the eastern YRD green technology diffusion network continued to grow and dominated the whole YRD region, but the intercity green technology transfer in this stage was opposite to that in 2015, showing patterns from east to west and from east to south, which were mainly transfers of green patents from Shanghai, Nanjing, Suzhou, and other cities to the west. In general, cities with higher innovation linkage intensity in these three years are basically centered on Shanghai, Suzhou, Hangzhou, Nanjing, Ningbo, Jiaxing, and cities with higher economic development levels. The intensity of green patent transfer linkage among cities generally shows the characteristics of intensiveness in the southeast and sparseness in the northwest. In addition, the direction of patent flow shifts from clustering in the east to spreading from the east to the central and western regions.

4.2. Model Estimation Results

Since the number of green patent transfers in the YRD in 2010 was so small, which would affect the robustness of the model, we only used the green patent data of 2015 and 2020 for regression. Table 3 shows the QAP regression results of the factors influencing green technology diffusion in the YRD in 2015 and 2020. The coefficients of environmental regulation are all positive and all significant at the 1% level, indicating that the stronger the spatial linkage of environmental regulation is, the greater the amount of green technology transfer between cities. In other words, our study shows that a high level of similarity in environmental regulations can facilitate green technology transfer within the YRD region. As the largest economic growth pole in China, the YRD region, which contains Shanghai, Jiangsu, and Zhejiang provinces, as early as 2004, jointly issued the Declaration on Regional Cooperation in the YRD to incorporate environmental cooperation into the regional economic integration strategy and make full use of market instruments to improve and develop environmental regulations. In 2007, 16 cities in the economically developed eastern and southern YRD signed the YRD Regional Cities (Changzhou) Cooperation Agreement, which established a general framework for the YRD to facilitate ecological compensation mechanisms. In 2016, the three provinces and one city of the YRD jointly published the Regional Linkage of Environmental Law Enforcement in the YRD Region Initiative to make cooperation in supervising environmental violations involving water, air and hazardous waste. In 2019, China issued the "Outline of the YRD Regional Integrated Development Plan", which prioritizes adherence to ecological and environmental protection and places great importance on the protection and restoration of the ecological environment. It can be understood that the environmental regulations in the YRD region are gradually improving, given the two main environmental regulations of incentives and penalties. Since then, the environmental regulations of the three provinces and one city in the YRD have a tendency toward integration, and the collaborative environmental management has become increasingly effective, which also promotes the intraregional flow of green technologies in the YRD, to a certain extent.

Table 3. QAP regression of influencing factors of green technology transfer in YRD.

Variables	2015		2020	
	Unstandardized Coefficient	**Standardized Coefficient**	**Unstandardized Coefficient**	**Standardized Coefficient**
ERR	0.533281 ***	0.269436 ***	2.120452 ***	0.216643 ***
GDP	1.685275 ***	0.866144 ***	4.569788 ***	0.474893 ***
IND	−0.889848 ***	−0.456892 ***	−3.562693 ***	−0.369811 ***
HUM	0.350277 ***	0.180017 ***	2.439780 ***	0.253540 ***
SRE	−0.145534 **	−0.074759 **	0.055620	0.005777
KNO	−0.893463 ***	−0.459295 **	−1.782901 ***	−0.185294 ***

Note: *** $p < 0.1$, ** $p < 0.05$.

In addition, we have some other findings. Urban economic development linkage promotes green technology flow within the YRD region. The stronger the urban economic development level linkages are, the more economic cooperation there is, which to a certain extent widens the opportunities for intercity green technology exchange and cooperation, thus promoting green technology transfer. Second, tertiary industry linkages did not promote intercity green technology transfer, while they had a suppressive effect. The possible reason is that green building technology is the most applied green patent category in China, and, when analyzing the spatial and temporal pattern of green technology flow in the YRD, we found that green building technology is the most popular technology in the market, which is why the growth of tertiary industry, represented by the information and communication industry and scientific research, does not promote green technology flow.

Third, human capital linkage can promote green technology transfer within the YRD region. Talent is the engine of scientific and technological progress and plays a prominent role in enhancing green technology innovation capacity. When educational human capital accumulates to a certain level, especially when the technological innovation effect of advanced educational human capital comes into play, human capital linkage would have a positive impact on green technology transfer in the YRD. Fourth, the government's scientific research support has negative influence on green technology transfer in the YRD region. The government's financial support for education and scientific research mainly promotes scientific research, rather than the specific application of green technology results. Therefore, more government support for scientific research and education does not necessarily facilitate green technology transfer. Fifth, there is a significant negative effect of innovation capacity linkage on green technology in the YRD. After 2015, although the green patent transfer among top cities, such as Shanghai and Suzhou, occupied the top position, many cities with a low number of green patent applications also had technology transfers with top cities. For example, in 2020, top cities such as Shanghai, Nanjing, Hangzhou, and Wuxi mainly played the suppliers' role in the patent transfer network, while cities with weak knowledge bases such as Anqing, Fuyang, and Bozhou obtained many green patents from top cities. In this regard, innovation capacity linkage does not impede intercity green technology transfer. This confirms the correctness of technology gap theory, which induces technology transfer to occur, i.e., cities with strong green innovation capabilities will transfer green technologies to cities with weaker green innovation capabilities.

5. Conclusions and Discussion

The relationship between environmental regulation and green technology diffusion is currently a core research topic in the environmental innovation field. In this paper, we measured the intercity green technology diffusion by the number of green patent transfers and carved the spatial and temporal patterns of green technology flows in the YRD. Then, we analyzed the impact of environmental regulation on green technology transfer with the help of the QAP model, from which we summarized the following findings.

First, from 2010 to 2020, green technology transfer in the YRD region mainly occurred in Shanghai, Hangzhou, Shaoxing, Suzhou, and Nanjing. The intensity of the green patent transfer linkage between cities generally shows the characteristics of intensiveness in the southeast and sparseness in the northwest, while the direction of patent flow shifts from clustering in the east to spreading from the east to the central and western regions. From the perspective of green patents, the ecological green integration of the YRD has not yet been realized and needs to be further developed [35]. Cities in the east and south lead the development of green technology transfer in the YRD. Meanwhile, the western and northern regions, such as Anhui Province, are the key "poverty alleviation" areas of green technology integration in the YRD.

Second, the regression results show that environmental regulation facilitates green technology diffusion within the YRD region. This is because the YRD region, as the leader of green development in China, reached a regional environmental governance agreement as early as 2004. Since then, environmental regulation regulations in the YRD region have been gradually improved. In 2019, the integrated green regional development of the YRD region was promoted to a national strategy. The YRD region has been at the forefront of green development in China, and its relevant laws and regulations are more mature, which is an important reason why environmental regulations play a strong role in promoting green technology diffusion within the YRD region.

In addition, we have some other interesting findings. First, tertiary sector linkages have a negative impact on the flow of intercity green technology. Green building technologies are the most dominant technologies in the market, so the growth of the tertiary sector, represented by the information and communication industry and scientific research, does not promote the flow of green technology. Secondly, human capital linkage has a facilitating effect on green technology transfer within the YRD region, because, when educational human capital accumulates to a certain level, the technological innovation effect of advanced educational human capital will, especially, come into play. Third, innovation capability linkage shows a negative effect on green technology transfer in YRD, which confirms the technology gap theory. Fourth, government research support has a negative effect on green technology flow within the YRD region.

In response to the above findings, we offer some suggestions. Firstly, the Yangtze River Delta region needs to increase green technology innovation investment collectively; the top cities of green technology innovation, especially, should help cities with weaker green technology innovation capacity through a multitype help mechanism, to narrow the technology gap between cities, while enhancing cities' green technology absorption and conversion capacity. Secondly, it is necessary to build the central role of Shanghai's green technology innovation in China by cultivating green technology innovation engine enterprises, improving its green technology innovation potential, and enhancing the radiation and driving ability of Shanghai on green technology innovation in the Yangtze River Delta. Finally, it is crucial for the Yangtze River Delta region to tailor (dynamically adjust) environmental regulations to local conditions. The Yangtze River Delta collaborative governance system should be further improved to avoid the "race to the bottom" that is caused by excessive differences in the intensity of environmental regulations between cities.

There are still some limitations in our study. First, it is, relatively, a single method to measure the environmental regulation of cities from the perspective of pollutant treatment, by synthesizing only the comprehensive utilization rate of general industrial solid waste, domestic sewage treatment rate, and harmless domestic waste treatment rate into comprehensive indicators, so building a richer environmental regulation evaluation index system is a future direction to be explored. Secondly, although China's green patents has been classified into six types according to the existing literature, there are still some environmental technologies that have not been taken into consideration, such as adsorption and cooling technology, advanced combustion technology, and emission reduction technology, so a broader green patent identification system should be established in the future. Thirdly, enterprises have a dominant position in green technology innovation and transfer. Combining enterprise heterogeneity (scale, industry, etc.) with the spatial and temporal characteristics of green technology diffusion and analyzing the influence of environmental regulation on the green technology transfer between enterprises and industries of different scales is the next issue to be studied. Finally, although we have divided the green technology categories, we have not explored the spatial and temporal characteristics of green technology transfer in each category or the influence of environmental regulation on the diffusion of green technology in different categories, which are also topics that needs to be studied in the future.

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Article

Spatial Distribution Characteristics and Driving Factors of Rural Revitalization Model Villages in the Yangtze River Delta

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Abstract: The scientific promotion of rural revitalization is an important issue in the context of global poverty reduction and sustainable development. For China, the largest developing country in the world, the construction of rural revitalization model villages has become an important measure to achieve agricultural and rural modernization and the coordinated development of urban and rural areas. Research on the rural revitalization model villages in China can provide guidance for the rural transformation development in other developing countries. In this paper, the Yangtze River Delta (YRD) was used as the study area, and the spatial differentiation characteristics and driving factors of 1621 rural revitalization model villages were analyzed using ArcGIS software and the geographical detector method. The results are as follows: (1) The multiscale spatial distributions of rural revitalization model villages in the YRD showed a weak agglomeration and disequilibrium characteristic. Anhui Province has the highest imbalanced distribution of model villages among different provinces in the YRD. (2) The model villages are the most densely distributed along the Yangtze River. Extending to the north and south from areas along the Yangtze River, the distribution of the model villages is first sparse then dense. Model villages agglomerate mainly along rivers and lakes, areas close to traffic arteries and the middle areas of suburban. (3) The spatial differentiation of rural revitalization model villages is the result of the combined effect of multiple factors, and the driving factors also showed significant spatial heterogeneity. The most important driving factors of the spatial differentiation of the model villages of the YRD, Jiangsu, Zhejiang, and Anhui are social development and government intervention, transportation accessibility and economic development, resource endowment and natural conditions, and transportation accessibility and government intervention, respectively. This study has practical significance for optimizing the spatial pattern of rural revitalization model villages in the YRD and facilitating high-quality rural revitalization.

Keywords: rural revitalization model village; spatial differentiation; driving factors; geographical detector; the Yangtze River Delta

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1. Introduction

Rural areas are indispensable units of the urban–rural system, which have important functions, such as agricultural production, ecological maintenance, and cultural inheritance [1]. However, under the impact of long-term industrialization and urbanization, rural decline has become a global challenge [2]. Problems in rural areas, such as population loss, economic recession, and the widening of the urban–rural gap, have become increasingly prominent, severely constraining regional sustainable development [3]. Both developed and developing countries around the world are actively exploring measures that suit local conditions to promote rural revitalization [4], such as the construction of central villages in England and the Rural Revitalization Plan in France in the 1960s, and the Saemaul Undong (New Village Movement) of South Korea and the One Village One Product movement of Japan in the 1970s [5–7]. These programs have promoted the construction of rural infrastructure, revitalized rural land resources, and improved rural production and living conditions. The implementation of these programs has reversed the decline of rural areas effectively by attracting people back to the rural and promoted urban–rural coordination and high-quality development [8].

Under the guidance of the macro policy of "Economic Construction as the Center of Socioeconomic Development" since the reform and opening up, China's local governments have implemented a series of urban-biased development measures to promote rapid economic growth. While creating a "growth miracle" for China's economy, the implementation has also brought about rural decline, characterized by environmental pollution, population migration, and agricultural decline [9]. Since the beginning of the 21st century, due to the tremendous negative impact of rural decline on regional sustainable development and the real demand for China's economy to shift to high-quality development, macroeconomic policies have gradually shifted from urban bias to urban–rural balance. Accelerating the promotion of rural revitalization has become the focus of the Chinese government and academia. In this context, the government has successively implemented macro strategies with Chinese characteristics, such as urban–rural coordination, new rural construction, urban–rural integration, new urbanization, and rural revitalization. The construction of model villages in particular has become an important path for local governments to implement the macro strategies of rural revitalization [10]. The local governments select a number of villages with a good development foundation and support them to improve their living environment and develop special industries through financial investment and land supply security. Through these measures, local governments try to create realistic model villages of rural revitalization. By summarizing and promoting the construction experience of these model villages, the construction of model villages can be extended from one locality to a larger area to realize territory-wide rural revitalization. The spatial distribution of model villages has become an important means of understanding the rural revitalization strategies and construction effects of various regions and has received extensive attention from all sectors of society.

In China, the number of villages is large while their spatial heterogeneity and development disparity are strong; therefore, a direct copy of the developed countries' path of rural revitalization that relies on a strong financial supply and the transfer of surplus rural labor is impractical [8]. Moreover, it is difficult to succeed by relying solely on the macro guidance of the central government; only through exploring and promoting localized experiences in different regions can China's rural revitalization be fully realized. The Yangtze River Delta (YRD) is one of the most dynamic economic regions in China while it has typical heterogeneity in rural development. The realization of rural revitalization becomes the main focus and challenge for the YRD to take the lead in realizing modernization and high-quality development on the basis of "integration". The study of the spatial distribution pattern and driving factors of rural revitalization model villages in the YRD can not only clarify the actual situation and experience of rural revitalization in China's economically developed areas but also help develop rural revitalization strategies in accordance with local conditions in the YRD. Using the rural revitalization model villages in three provinces (Jiangsu, Zhejiang, and Anhui) and one city (Shanghai) in the YRD as the research object, this paper analyzed the spatial distribution characteristics and evaluated the separate effects and interaction effects of different factors on the spatial differentiation of model villages to identify the main driving factors. Furthermore, this paper discussed how to build a collaborative governance path among multiple entities such as community and government in China to promote the sustainable development of the model villages. This study addressed the following questions: (1) What are the spatial distribution characteristics of the rural revitalization model villages in the YRD? (2) What are the driving factors of the spatial differentiation of the rural revitalization model villages in the YRD, including the composition of the driving factors and the magnitude of separate effects and interaction effects of different factors? (3) How do the main driving factors affect the distribution of model villages? This research can not only enrich the theoretical system of rural revitalization in China but also provide an example of rural revitalization for other developing countries and regions.

2. Literature Review

2.1. Studies on the Spatial Distribution Pattern of Model Villages

As model villages are typical geographical units of rural development, scholars have carried out much research on them with rich results. These studies have focused on the development process of demonstration villages [11], the location and spatial pattern [12], influencing factors and formation mechanism [13], and spatial agglomeration and diffusion [14]. In terms of the spatial distribution pattern, the academic community has carried out rich research on relevant issues from multiple angles, mainly describing the spatial distribution types, the spatial equilibrium situation, aggregation characteristics, and spatiotemporal evolution characteristics of different types of demonstration villages [15,16]. Some studies also use case villages to explore the spatial structure of a village and its reconstruction characteristics during the rural transformation development at a micro scale [17]. The objects of these studies include demonstration villages of protection of traditional culture and characteristic development. The former comprises traditional villages [18], while the latter includes rural tourism destinations [15], agricultural characteristic villages [19], and specialized villages [20]. Study areas mainly focus on the national level [19,21]. The research methods are based mainly on geographic information technology and statistical analysis methods, including the average nearest neighbor index (NNI), geographic concentration index, disequilibrium index, kernel density-estimation (KDE) method, fractal grid dimension analysis, and spatial autocorrelation analysis [18–21]. Research on the characteristic development demonstration villages, such as key rural tourism villages and "One Village One Product (OVOP)" demonstration villages, provides a reference for exploring the spatial differentiation characteristics of rural revitalization model villages.

The results of theoretical analysis and empirical research show that the construction of demonstration villages can significantly improve the living conditions of villagers, promote economic growth of the villages, and stimulate the development of surrounding rural areas. However, due to the constraints of the natural environment, resource endowments, and macroeconomic policies, the spatial distribution of the demonstration villages is disequilibrium, showing significant spatial agglomeration characteristics [22]. The demonstration villages are concentrated mainly in economically developed, densely populated, and resource-rich areas; besides, they tend to locate around large or medium-sized cities and the main road network [15]. For example, studies of demonstration villages in China show that economically developed areas, such as the YRD and the Beijing–Tianjin–Hebei region, are the agglomeration areas of key rural tourism villages and OVOP demonstration villages. However, the agglomeration characteristics of different types of model villages are starkly different and are closely related to the resource endowment and industrial development [21]. The spatial pattern of agricultural development demonstration villages is highly consistent with the regional agricultural strategic pattern [19]; tourism development demonstration villages mainly surround large and medium-sized cities, are distributed near scenic areas and agglomerated in areas with unique cultural, natural, and social resources [15]; model villages for industrial development are concentrated mainly in areas with a flat terrain and convenient transportation which afford convenient distribution of materials and products. Although the range of the spatial distribution of model villages spreads over time, the degree of spatial agglomeration increases gradually [21].

2.2. Studies on the Driving Factors of the Spatial Distribution of Model Villages

In terms of research methods, previous studies mainly focus on qualitative descriptions; that is, by summarizing the characteristics of industrial development, policy environment, population agglomeration, and culture of the model village agglomeration areas, the effects of the above factors on the distribution of model villages are analyzed [23]. With the rapid development of information technology, methods such as ArcGIS software-based overlay analysis and buffer analysis have been widely used to explore the spatial relationships between the model villages and geographic elements, such as the terrain and rivers, and human elements, such as roads, cities and scenic spots [18,22]. In addition, some studies have used the geographic connection rate to analyze the spatial consistency between the distribution of demonstration villages and gross domestic product (GDP), residents' consumption, scenic spots and historic villages [15,24]. In recent years, with gradual improvements in spatial measurement and other methods, the geographical detector analysis method has been widely used to identify the driving factors of the spatial distribution pattern of various geographical phenomena, quantitatively detecting the explanatory power of factors such as elevation, river network density, per capita GDP, highway density, and population density on the spatial distribution of model villages [20,22].

The results show that the spatial distribution of different kinds of demonstration villages is affected mainly by factors such as natural conditions, resource endowments, economic development, social development, the policy environment, location, and transportation, but the main driving factors of different types of model villages are different. Among them, the driving factors for specialized villages include mainly elite farmers, geographical factors, resource characteristics, government behavior, socioeconomic environment, and technology [20]. The spatial distribution of characteristic agricultural villages is closely related to factors including rural population, land and industrial development level [19]. The spatial distribution of tourism model villages is affected mainly by factors such as topography, resource endowment, location, transportation conditions, tourist source market, economic development, policy and innovation environment, and other factors, such as climate, population and education, cannot be ignored [15,22]. The pilot villages in the Beautiful Village Initiative are affected mainly by factors such as the locations, traffic conditions, resource distribution, economic development, and policy environment [21]. In addition, as a background constraint factor in economic and social development, natural conditions, such as the topography and landforms, affect the location and development of rural settlements, thereby affecting the spatial distribution of model villages [25].

2.3. Studies on Rural Revitalization and Sustainable Development Paths

Around the world, the paths to rural revitalization are diverse and controversial and have transformed from exogenous development into endogenous development and then into new endogenous development [26]. In the 1960s and 1970s, rural revitalization in Europe and some other countries in the Northern Hemisphere mainly followed an exogenous development path, i.e., hollowed out and depleted rural areas were developed with extensive involvement and stimulation of urban capital, technology, and talent [27]. However, driven by the profit-seeking nature of capital, many foreign entities turned to plundering rural resources, which exacerbated rural decline and limited autonomous local development [28]. In response to this predicament, the endogenous development path began to receive attention and was widely used to reverse the decline in rural areas [29]. In the 1990s, the Links between Actions of Rural Development (LEADER) of the European Union (EU) and its subsequent projects advocated the full use of the creativity of rural communities and emphasized the right of local community to decide on development options, to control the development process, and to enjoy the benefits of development [30]. Due to the imbalanced participation capacity of local communities, this type of practice, which emphasizes the internal strength of the village, has been criticized. "It is unrealistic to rely solely on local actors to implement 'pure' endogenous development without the help of external forces" [31]. On this basis, a new endogenous development path has emerged, which advocates that based on a "bottom-up" approach of community leadership, a collaborative governance network with external actors should be established to rationally and effectively use external actors and resources to enhance endogenous development capacity [32].

Through long-term practical exploration, rural revitalization in developed countries has gradually formed a practical path of "policy support-technical support-social participation-comprehensive evaluation", which emphasizes farmers' entrepreneurial spirit and building community networks as the keys to rural revitalization [33,34], adopts the "government support for agriculture" approach, and uses both legislative and enterprise cooperation paths [35]. The government and rural communities are widely considered to play important roles in rural revitalization [36]. In the past, rural construction in China was led mostly by the government or enterprises. Although the short-term development performance is outstanding, it is difficult for this approach to benefit all villages and stimulate villagers' enthusiasm to participate, which is not conducive to the sustainable development of rural areas. Studies generally indicate that the current rural revitalization in China should further enhance the bottom–up initiative of the villagers and establish a new endogenous development path with the participation of both villagers and foreign entities. However, studies on community participation have suggested that there is very little actual community participation in developing countries [37]. The participation of rural communities in China is mainly symbolic and passive, and the main constraints are the lack of effective participation channels, villagers' low level of knowledge, and lack of awareness and effective ability to participate [38]. Given these issues, to construct a new endogenous rural revitalization path in developing countries such as China, a collaboration governance network between internal and external entities (i.e., rural community and the government) should be established, and the level of rural community participation should be improved.

2.4. Summary of Literature Review

Although existing studies have focused on the spatial differentiation of various demonstration villages and have achieved some results, there are still some limitations in terms of research objects, research scales, and methods of identifying driving factors. In terms of research objects, the existing research mainly focuses on a single dimension of rural development, such as economic growth or improvement of human settlements. In fact, the construction of rural revitalization model villages emphasizes the comprehensive development of the rural system, spanning multiple dimensions, such as the human settlements, economy, culture, and governance, which is different from living environmental improvement model villages and characteristic development demonstration villages. The research shows that there are significant differences in the agglomeration characteristics of various demonstration villages, and it is necessary to explore the spatial distribution pattern of rural revitalization model villages.

In terms of research scales, previous studies have been mainly conducted at the national scale. However, at different spatial scales, the generation mechanisms of geographic phenomena are quite different [24]. Moreover, the types of regions in China are diverse and complex. Existing research cannot meet the needs of understanding the spatial differentiation characteristics of demonstration villages in different types of regions, nor can they provide a scientific basis for adopting differentiated rural revitalization strategies based on their respective regional characteristics. The YRD is a developed region with high-density population and rich natural resources. Besides, it is a pioneer of institutional reform and policy innovation in China, which offers a favorable opportunity for the construction of various demonstration villages. The YRD is the high-density area of various model villages while it is also a region with significant heterogeneity of urban–rural integration. However, the spatial differentiation characteristics of model villages within this type of region have received little attention. Therefore, it is necessary to identify the spatial distribution characteristics and driving factors of the rural revitalization model villages in the YRD to deepen the understanding of the distribution rules of rural revitalization model villages in different types of regions and at different spatial scales.

In terms of identifying methods of driving factors, a few studies have used the factor detection method of geographical detector to analyze the individual effects of different factors on the spatial differentiation of model villages, and combine the influence of different factors according to the principle of maximum value. However, the effect of multiple factors acting together may be greater or less than the effect of a single factor; therefore, it is necessary to improve the methods adopted to analyze the interaction effect of different factors on the spatial differentiation of model villages. By using the factor detection module and interaction detection module of the geographical detector, this study not only can quantitatively measure the individual influence of different factors, but also can measure the interaction influence of different factors more precisely, which helps to identify the main drivers of spatial differentiation in model villages more accurately.

3. Study Area and Methods

3.1. Study Area

The study area is the YRD. According to the Outline for the Yangtze River Delta Regional Integration Development Plan issued by the Central Committee of the Communist Party of China and the State Council in 2019, the YRD covers the entire region of Shanghai, Jiangsu, Zhejiang, and Anhui. This document provides an important basis for selecting this region for study (Figure 1). YRD region has a long history of agricultural cultivation and is a pioneer in exploring rural transformation development paths. In 2021, the total GDP of the YRD region was 24.47 trillion yuan, accounting for approximately 1/4 of China's GDP; the total population was approximately 235.21 million, and the urbanization rate exceeded 70%.

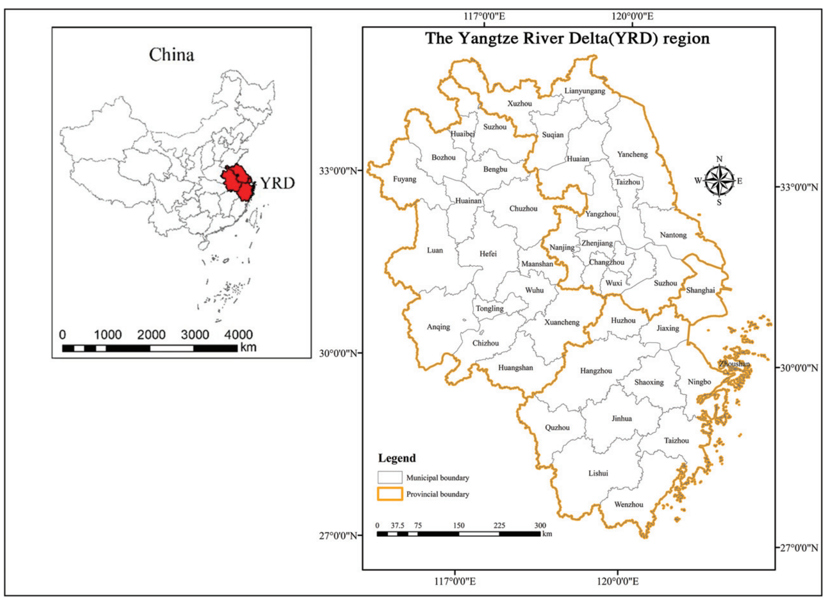

Figure 1. Study area.

Since the reform and opening up, the globalization, industrialization, and urbanization in the YRD have been accelerating, and rural areas have undergone multiple rounds of reconstruction. In the 1980s, the Southern Jiangsu model, characterized by the emergence of township enterprises, promoted the rapid development of rural urbanization; since 2005, with a new understanding of rural values and the transformation of the consumption structure, the rapid development of characteristic towns and villages as a link between urban and rural areas has radiated and driven the development of the surrounding rural areas. With the proposal of the rural revitalization strategy by the central government in 2017, local governments in the YRD have formulated corresponding implementation plans and have actively constructed various rural revitalization model villages.

However, with the expansion of the planning scope of the YRD region and the regional rise and fall caused by the free flow of resource elements, the heterogeneity of rural development within the YRD is significant. In the region from Hefei to Nanjing and to Shanghai and the megaregion along the coast of Hangzhou Bay, the high level of urban development has prompted the flow of resources from the city to the surrounding villages which stimulate the rapid development of rural areas. In contrast, driven by rapid urbanization, the urban–rural development gap in northern Jiangsu, Anhui, and inland Zhejiang continues to widen. In the context of integration, when pursuing region-wide rural revitalization, the YRD still faces the challenge of a wide gap in rural development within the region.

3.2. Research Samples and Data

In this study, the sample rural revitalization model villages in the YRD were selected according to the following criteria. First, the sample model villages were selected from rural revitalization projects of the same kind, grade, and level created in various places within the same period of time after the rural revitalization strategy implementation. Second, the project must focus on the systemic nature of rural revitalization, and the content should cover different aspects, such as improvement of living environment and development of the economy and society. Based on these criteria, this study selected the provincial model village projects recognized by the local governments in the YRD since 2017, i.e., the featured countryside in Jiangsu, the beautiful and livable model village in Zhejiang, the key model village of the beautiful villages project in Anhui, and Shanghai's rural revitalization model village (Table 1).

Jiangsu began to promote the construction of featured countryside in 2017 and assessed and identified pilot villages in 2019. By the end of 2021, 446 provincial featured countryside pilot villages had been identified. Since 2018, as an upgraded version of the beautiful villages, the standard for beautiful villages in Zhejiang has shifted from the comprehensive improvement of the village environment to rural revitalization led by green development. By the end of 2021, 551 provincial-level beautiful and livable model villages had been created. The construction of key model villages of the beautiful villages project in Anhui started in 2018 and began to be assessed and recognized in 2019. By the end of 2021, Anhui had identified 544 provincial-level key model villages. Since 2018, Shanghai has selected rural revitalization model villages, and a total of 80 villages were created by the end of 2021. The final samples selected in this study were the 1621 model villages identified starting from the implementation of the rural revitalization strategy to the end of 2021 (Figure 2). The model villages in Shanghai, Jiangsu, Zhejiang, and Anhui account for 4.94%, 27.51%, 33.99%, and 33.56% of the total number of model villages in the YRD, respectively.

Based on the official websites of relevant government departments of Jiangsu, Zhejiang, Anhui, and Shanghai, this study obtained a list of model villages and used the Baidu Map coordinate selection system to obtain the location coordinates of each model village. The data coordinates were imported into ArcGIS 10.8, and after alignment and projection, a database of spatial attributes of the rural revitalization model villages in the YRD was established. The basic geographic data were from the database of the National Geomatics Centre of China; the road traffic data were from amap.com; and the socioeconomic development data were from the official websites of the National Bureau of Statistics, the Bureau of Statistics of various provinces and cities and the Ministry of Housing and Urban–Rural Development.

Table 1. The sample rural revitalization model villages in the YRD [1].

Sample	Construction Requirements	Target Number		Existing Number in 2021
		in 2022	in 2025	
Rural Revitalization Model Village in Shanghai	Optimizing village layout, improving rural landscape, improving living environment, increasing efficiency of agricultural development, and promoting rural governance	90	150	80
Featured Countryside in Jiangsu	Highlighting rural culture, protecting the ecological environment, cultivating industrial development, and enhancing rural vitality	500	1000	446
Beautiful and Livable Model Village in Zhejiang	Promoting the prosperity of rural industries, livability of living environment, the moral and ethical standards of the rural, efficiency of governance and the prosperity of life to a new level, and improving the quality of beautiful rural areas overall	500	1000	551
Key Model Villages of the Beautiful Village Project in Anhui	Promoting village infrastructure, improving the living environment, improving rural public services, strengthening the construction of rural civilization, developing the industry according to local conditions, strengthening the collective economy, and strengthening the leadership of grassroots party organizations	-	1000	544

[1] Source: Collated from policy and planning documents of Jiangsu, Zhejiang, Anhui, and Shanghai, namely, The Rural Revitalization Strategic Plan (2018–2022), Opinions on the Implementation/Promotion of Rural Revitalization Strategy, The 14th Five-Year Plan for the Modernization of Agriculture and Rural Areas, and The 14th Five-Year Plan for Rural Revitalization, respectively.

3.3. Research Methods

3.3.1. Nearest Neighbor Index (NNI)

Model villages are represented as point-like elements on a macroscopic scale, and the spatial distribution type of point-like elements can be determined by the NNI [19]. The calculation formula is as follows:

$$R = \frac{r_1}{r_E} = 2\sqrt{D} \tag{1}$$

where r_1 is the actual nearest neighbor distance; r_E is the theoretical nearest-neighbor distance; and D is the point density. When $R = 1$, the spatial distribution of the model villages shows a random pattern; when $R > 1$, the model villages tend to be evenly distributed; when $R < 1$, the model villages tend to be agglomerated.

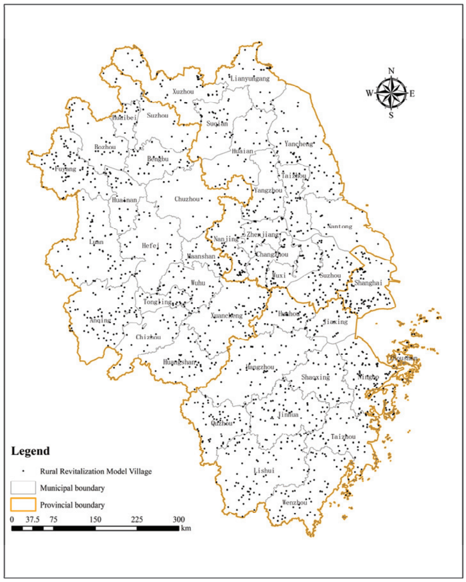

Figure 2. Distribution map of rural revitalization model villages in the YRD.

3.3.2. Disequilibrium Index

The disequilibrium index analyses the balance of the distribution of model villages at the urban scale [18], and the calculation formula is:

$$S = \frac{\sum_{i=1}^{n} Y_i - 50(n+1)}{100 \times n - 50(n+1)} \tag{2}$$

where n is the number of regional units and Y_i is the ith cumulative percentage when the proportion of model villages in the designated area to the total model villages in the study area is ranked in descending order. S is usually between 0 and 1. $S = 0$ indicates that the model villages are evenly distributed in each regional unit, and $S = 1$ indicates that the model villages are concentrated in a certain regional unit.

When calculating the disequilibrium index of the model villages in the YRD, Jiangsu, Anhui, and Zhejiang, n is the total number of prefecture-level cities and municipalities; when calculating the disequilibrium index of the model villages in Shanghai, n is the total number of prefecture-level urban districts.

3.3.3. Kernel Density Estimation (KDE)

KDE can intuitively reflect the agglomeration degree and areas of the model villages [22]. This study used the KDE to measure the spatial agglomeration characteristics of the model villages. The calculation formula [34] is:

$$f_n(x) = \frac{1}{nh} \sum_{i=1}^{n} k\left[\frac{1}{n}(x - x_i)\right] \tag{3}$$

where $k(x)$ is the kernel function; $(x - x_i)$ is the estimated distance from model village x to sample model village x_i; n is the number of all model villages; and $h > 0$ is the bandwidth. The larger $f_n(x)$ is, the denser the distribution of model villages is.

3.3.4. Geographical Detector

Geographical detector is a new statistical method for detecting spatial heterogeneity and revealing the underlying driving factors and can detect both numerical data and qualitative data without linear assumptions [39]. In this paper, a geographical detector was used to detect the driving factors of the spatial differentiation of the model villages. The q statistic can measure spatial heterogeneity, detect explanatory factors, and analyze the interaction of variables. The calculation formula is:

$$q = 1 - \frac{1}{N\sigma}\sum_{n=1}^{L} N_h \sigma_h^2 = 1 - \frac{SSW}{SST} \quad (4)$$

where L is the number of categories of influencing factors; N_h and N are the number of units in class h and the study area, respectively; σ_h^2 and σ^2 are the variance in class h and the Y value of the study area, respectively. SSW and SST are the sum of the intraclass variance and the total variance in the study area, respectively. The value of q is [0, 1]; a larger q means a higher explanatory power of the index regarding the spatial distribution of the model villages.

4. Results

4.1. Spatial Distribution Characteristics

4.1.1. Spatial Distribution Balance

The NNI analysis of the rural revitalization model villages in the YRD showed that the actual average nearest-neighbor distance was 6.89 km, the theoretically expected nearest-neighbor distance was 8.85 km, and the value of R was 0.78, indicating that the model villages in the YRD showed a weak agglomeration distribution. Based on Equation (2), the value of the disequilibrium index was 0.27, indicating that the distribution of the model villages in the YRD was not even at the urban scale, but the degree of imbalance was relatively low. Each city has a certain number of model villages, which indicates that the spatial development of model villages in the YRD is relatively good.

The difference in spatial equilibrium characteristics of the model villages in different provinces is relatively small. The NNI of the model villages in each province was basically between 0.7 and 0.8, and the disequilibrium indexes were all greater than 0 but were small, indicating that the model villages of all provinces had a weak agglomeration and disequilibrium distribution (Table 2). Among them, the spatial disequilibrium of model villages in Anhui was slightly higher than that in Shanghai, Jiangsu, and Zhejiang. For Jiangsu, Zhejiang, and Shanghai, first, there is a solid foundation for rural development, and the establishment of model villages has good material conditions and industrial foundations. Second, local governments have accumulated rich experience in rural transformation development, which helps quickly create more model villages. Finally, the economy is relatively developed, and the local government's annual budget is high. Therefore, local governments can invest more funds and resources in rural areas, which would strongly support the simultaneous construction of model villages in the region. For Anhui, first, the rural development level is relatively low; second, limited by the economic development level and the local government's annual budget, local governments provide less funding for the construction of model villages than in Jiangsu, Zhejiang, and Shanghai; therefore, it is difficult for Anhui to support the intensive construction of model villages in various places simultaneously.

Table 2. The NNI and disequilibrium index of rural revitalization model villages in three provinces and one city in the YRD.

Province	Jiangsu	Zhejiang	Anhui	Shanghai
Number of prefectures	13	11	16	16
Distribution density (number/10,000 km^2)	43.38	52.38	38.56	99.30
NNI	0.71	0.79	0.80	0.81
Disequilibrium index	0.22	0.24	0.28	0.22

4.1.2. Spatial Distribution Density

KDE analysis reveals the spatial differentiation pattern of the rural revitalization model villages in the YRD. The results showed that the high-density areas of the model villages were independent and obvious, and three high-density areas and six secondary high-density areas were formed (Figure 3). The three high-density areas are as follows: (1) the adjacent areas of Shanghai, Suzhou, and Jiaxing included Shanghai suburbs, main urban area of Suzhou, Kunshan, and Jiashan County; (2) the Nanjing–Wuxi–Changzhou joint area in Jiangsu Province, which takes the national pilot area for urban–rural integrated development (Nanjing–Wuxi–Changzhou joint area in Jiangsu Province) as the main body while covering Jurong County, Langxi County, and Bowang District; and (3) Fenghua District of Ningbo in the eastern part of Zhejiang. The six secondary high-density areas can be summarized as "one district, one belt and four cores": the southern Jiangsu secondary high-density agglomeration district includes the southern Jiangsu area and its adjacent areas, namely the suburban areas of Shanghai, the southwestern part of the central Jiangsu area and the eastern part of the southern Anhui area; the secondary high-density agglomeration belt in central Zhejiang includes the four cities of Ningbo, Taizhou, Jinhua, and Quzhou; the secondary high-density agglomeration core in central Jiangsu includes the contiguous area of Taizhou and Yancheng; the secondary high-density agglomeration core in northern Anhui includes the contiguous area of Fuyang and Bozhou; the secondary high-density agglomeration core of southwest Anhui includes mainly Anqing; and the secondary high-density aggregation core in Wanjiang city belt includes the contiguous areas of Tongling, Wuhu, and Chizhou.

In general, model villages are most densely distributed along the Yangtze River. Extending from the Yangtze River to the north and south, the distribution is initially sparse and then dense. The region along the Yangtze River has superior geography and transportation conditions, a relatively dense population and significantly higher levels of economic and rural development than other regions, providing strong material, manpower, financial, and market support for the establishment of model villages. This region is also a pioneer in institutional innovation, providing a favorable opportunity for the creation of model villages, and the distribution of model villages is the densest. The northern part of the YRD is dominated by plains, and Fuyang, Bozhou, Yancheng, and Taizhou are the main agricultural production areas. The agricultural development foundation is good, and the rural resident population is large, which provide a good industrial and social development foundation for the construction of model villages. In recent years, improved traffic accessibility in these regions has provided external conditions for the construction of model villages, and the distribution of model villages is relatively dense. The southern part of the YRD has a superior ecological environment and historical and cultural resources. The central area of Zhejiang has comparative advantages in terms of rural resident population and rural financial expenditure, providing resources and labor advantages for the construction of model villages. The distribution of model villages in this region is also relatively dense.

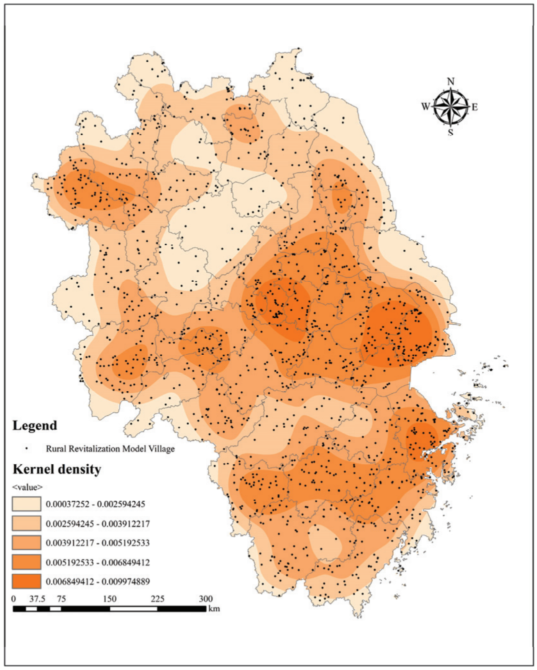

Figure 3. Kernel density map of rural revitalization model villages in the YRD.

4.1.3. Spatial Distribution Location

From the perspective of location preference, the distribution of rural revitalization model villages in the YRD has the following characteristics: (1) The model villages are characterized by their "proximity to major traffic arteries". The buffer analysis showed that the closer the areas were to the highway and the main road, the greater the number of model villages was; conversely, the greater the distance were, the lower the number of model villages was (Figure 4). Seventy percent of the model villages are distributed within 5 km of the main road network. (2) The model villages are less distributed in the suburbs and outer suburbs of the city and more distributed in the central suburbs. As the distance from the city increases, the number of model villages first increases and then decreases (Figure 5), and the number of model villages within 30–40 km of the city is the largest. In areas that are too close to cities, the possibility of rural urbanization is relatively high, and the total number of villages is small; in areas that are too far from cities, it is difficult for the villages to experience the driving force of urban development, which is not conducive to the establishment of model villages. More than 65% of the model villages are distributed within 50 km of the city, which has good traffic accessibility and can benefit from the functional radiation of the city. Approximately 32% of the model villages are located 50 km away from the city, mainly in areas with rich ecological or cultural resources and unique rural features. (3) The model villages tend to be distributed along rivers and lakes (Figure 6). Analysis by direct superposition of the distributions of the river network and the model villages showed that 40% and 65% of the model villages were within 5 km and 10 km of the river system, respectively. For example, the adjacent areas of Shanghai, Suzhou, and Jiaxing are located in the Taihu Lake Basin and the estuary of the Yangtze River, the secondary high-density agglomeration cores of southwest Anhui and Wanjiang City Belt are located along the Yangtze River, and the secondary high-density agglomeration core of northern Anhui is close to the Huaihe River and its tributaries.

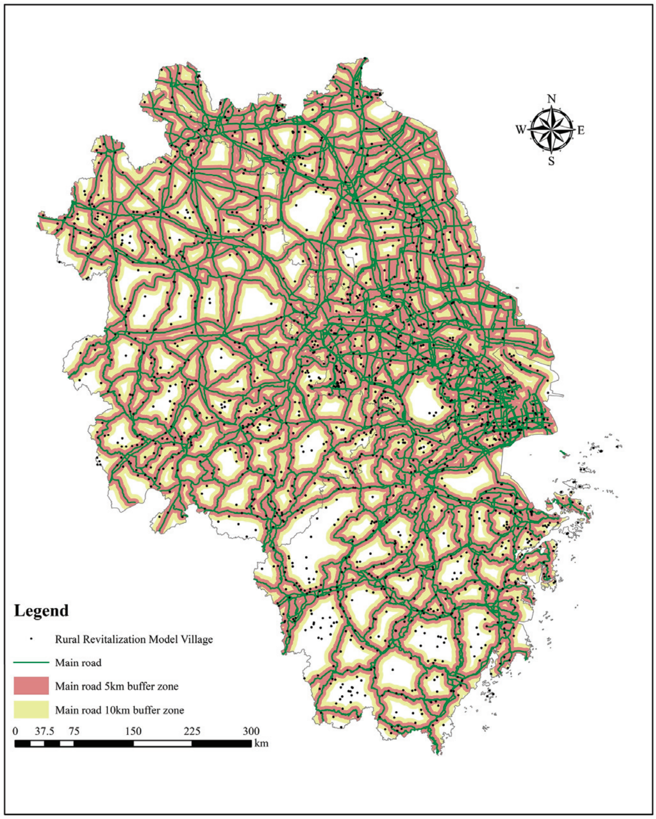

Figure 4. Major roads buffer zone and rural revitalization model villages in the YRD.

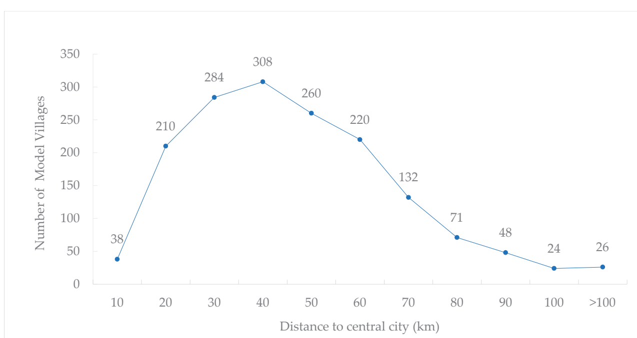

Figure 5. Curves of the number of rural revitalization model villages and the distance to central city in the YRD.

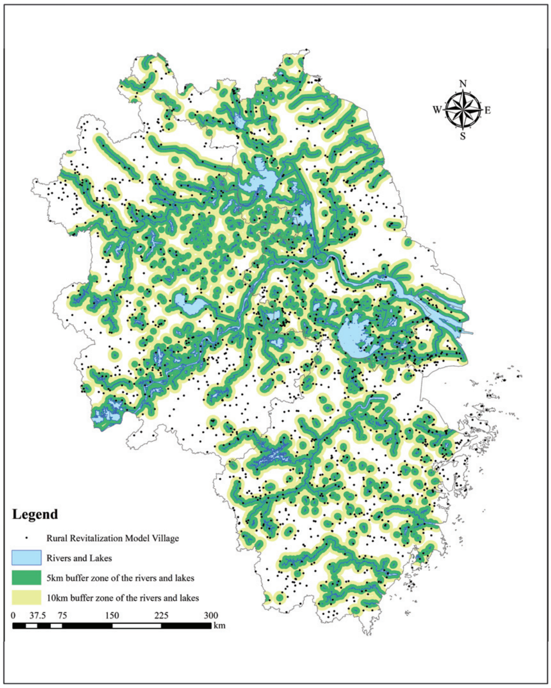

Figure 6. Water system buffer zones and rural revitalization model villages in the YRD.

4.2. Driving Factors of Spatial Differentiation of Model Villages

4.2.1. Construction of the Index System of Driving Factors

Based on relevant research and the actual situation of rural revitalization model villages, the availability of data, and the scientific method, this study focused on six types of factors, namely natural conditions, resource endowment, transportation accessibility, economic development, social development, and government intervention. Twelve highly representative indicators were used to identify the driving factors of the spatial distribution of the model villages (Table 3).

Table 3. The index system of the driving factors.

Driving Factors	Selected Index	Interpretation of the Variable
Natural conditions	Elevation (X1) River network density (X2)	Vertical height to the reference plane (m) River network area/km^2
Resource endowment	Distance to level 5A scenic area (X3) Number of traditional villages (X4)	Distance between the model village and level 5A scenic area (km) Number of traditional villages in each city (number)
Transportation accessibility	Distance to surrounding cities (X5) Road network density (X6)	Distance between the model village and the urban area (km) Length of highways and urban arterial roads/km^2
Economic development	GDP per capita (X7) Disposable income of farmers (X8)	Per capita GDP of each city (yuan) Disposable income of farmers in each city (yuan)
Social development	Population density (X9) Rural resident population (X10)	Number of permanent residents in each city/km^2 Rural resident population in each city (10,000 people)
Government intervention	Rural fiscal expenditure (X11) Public road mileage (X12)	Sum of general public expenditure of each county within the scope of the city (100 million yuan) Total public road mileage at the end of the year in each city (km)

4.2.2. Driving Factors of the Spatial Differentiation of Model Villages in the YRD

The geographical detector analysis showed that, except for elevation, the remaining 11 factors all had a significant impact on the spatial differentiation of the rural revitalization model villages in the YRD, but the influences of different factors were different (Table 4). From the perspective of a single factor, factors, such as road network density, farmers' disposable income, per capita GDP, and population density have the greatest impact on the spatial differentiation of the model villages; the effects of factors such as river network density, public road mileage, distance to level 5A scenic area, the number of traditional villages, and rural fiscal expenditures are relatively large; the explanatory power of factors such as rural resident population and distance from surrounding cities is small; and the effect of elevation is not significant. The interaction effect detection results of factors X1 and X2, X3 and X4, X5 and X6, X7 and X8, X9 and X10, and X11 and X12 were analyzed to obtain the explanatory power of the six types of factors on the spatial differentiation of model villages in the YRD, as shown in Table 5. Social development and government intervention are the most important driving factors in the spatial differentiation of model villages in the YRD. Economic development and transportation accessibility are the important driving factors, while resource endowment and natural conditions are normal driving factors.

Table 4. The explanatory power of various factors on the spatial differentiation of the model villages in the YRD.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
q value	0.003	0.216 *	0.183 *	0.180 *	0.096 *	0.331 *	0.299 *	0.304 *	0.288 *	0.109 *	0.144 *	0.211 *

* Indicates significance at the 1% level.

Table 5. Interaction effect detection results of different driving factors in the YRD.

Driving Factors	Natural Conditions	Resource Endowment	Transportation Accessibility	Economic Development	Social Development	Government Intervention
Interaction factors	X1 ∩ X2	X3 ∩ X4	X5 ∩ X6	X7 ∩ X8	X9 ∩ X10	X11 ∩ X12
q value	0.31	0.37	0.43	0.44	0.55	0.52

Overall, the spatial differentiation of the rural revitalization model villages in the YRD is the result of the combined effect of multiple factors. Because the construction of model villages has strong political significance, local government intervention plays a key role in guiding and promoting the construction of model villages and has the most important impact on the spatial differentiation of model villages. In the context of the continuous strengthening of the concept of "people-oriented governance" by the Chinese central government, people-related social development factors are also decisive driving factors in the spatial differentiation of model villages. The level of economic development and transportation accessibility affect the distribution of the model villages by affecting the factor input, rural accessibility, and the level of urban–rural factor flow and market connectivity. Although the natural conditions and resource endowments, which are the objective environmental factors, are the basic conditions for the formation and development of villages, they have little impact on the spatial differentiation of rural revitalization model villages in the YRD, which may be related to the low variation in the natural environment among cities in the study area.

4.2.3. Heterogeneity of the Driving Factors in Each Province [1]

The explanatory power of each factor regarding the spatial differentiation characteristics of the model villages in different provinces is different (Table 6). Additionally, the main driving factors of the spatial distribution characteristics of the model villages in different provinces are also different. The main driving factors in Jiangsu are the disposable income of farmers, public road mileage, rural fiscal expenditure, population density, river network density, road network density, per capita GDP, and rural resident population. The main driving factors in Zhejiang are rural fiscal expenditure, rural resident population, river network density, rural disposable income, population density, per capita GDP, number of traditional villages, and public road mileage. The main driving factors in Anhui are the road network density, per capita GDP, and river network density, and factors such as rural resident population, public road mileage, farmers' disposable income, and rural fiscal expenditure also have a certain explanatory power. Based on the explanatory power of interactions of factors (Table 7), the dominant factors in the spatial differentiation of the model villages in Jiangsu, Zhejiang and Anhui are as follows: transportation accessibility and economic development, resource endowment and natural conditions, transportation accessibility, and government intervention, respectively.

Table 6. The explanatory power of various factors on the spatial differentiation of the model villages in each province of the YRD.

Province	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
Jiangsu	0.006	0.358 *	0.156 *	0.234 *	0.160 *	0.355 *	0.354 *	0.450 *	0.365 *	0.334 *	0.381 *	0.441 *
Zhejiang	0.010 *	0.275 *	0.020 *	0.232 *	0.026 *	0.173 *	0.237 *	0.266 *	0.261 *	0.309 *	0.324 *	0.209 *
Anhui	0.012 *	0.258 *	0.041 *	0.136 *	0.042 *	0.304 *	0.280 *	0.185 *	0.095 *	0.194 *	0.164 *	0.188 *

* Indicates significance at the 1% level.

Table 7. Interaction effect detection results of different driving factors in each province of the YRD.

Driving Factors	Natural Conditions	Resource Endowment	Transportation Accessibility	Economic Development	Social Development	Government Intervention
Jiangsu	0.435	0.364	0.544	0.475	0.471	0.466
Zhejiang	0.339	0.421	0.333	0.276	0.324	0.324
Anhui	0.331	0.291	0.400	0.328	0.227	0.370

The comparison of the influence of different driving factors on the spatial differentiation of the model villages in each province shows that transportation accessibility is the most important driving factor in Jiangsu and Anhui, and it also has relatively strong explanatory power for the spatial differentiation of model villages in Zhejiang; the dominant factor is road density. Resource endowment is the most important driving factor in Zhejiang, however, it has little influence on the spatial differentiation of model villages in Jiangsu and Anhui, and the dominant factor is traditional villages. Economic development level is the comparatively important driving factor in Jiangsu and Anhui while it has relatively weak explanatory power for the spatial differentiation of the model villages in Zhejiang; the dominant factors are per capita GDP and farmers' disposable income. Social development level is the comparatively important driving factor in Jiangsu and Zhejiang while it has relatively weak explanatory power in Anhui; the dominant factors are regional population density and rural resident population size. Government intervention and natural conditions have relatively strong explanatory power for the spatial differentiation of the model villages in each province, and the dominant factors are rural fiscal expenditure, public road mileage, and river network density.

4.2.4. Influencing Mechanism of the Main Factors on the Spatial Distribution of Model Villages

The factors that exert a strong influence on the spatial differentiation of model villages in the YRD and each province are river network density, per capita GDP, and farmers' disposable income. For areas with a dense river network, the water resources are abundant, and the transportation is convenient, so they are suitable for agricultural planting and villagers' lives. Such areas tend to have large numbers of villages and also offer conditions for the development of characteristic agriculture and rural tourism, which is conducive to constructing more model villages. Areas with high GDP per capita tend to have relatively high levels of economic development, which can provide more sufficient and stable funding for the construction of model villages. Residents in these areas have a greater demand for high-value-added rural products, such as ecological agricultural products, tourism, and cultural and creative products, providing a broader market space for industry development of the model villages. For areas where farmers have high disposable income, rural construction often starts early, and the foundation for rural development is solid. The villages in such areas not only are closer to the standards of the model villages but also have richer experience in rural construction, which is conducive to the rapid development of model villages.

Factors that have a strong impact on the spatial differentiation of model villages in the YRD and most provinces are road network density, population density, public road mileage, and number of traditional villages. Convenient transportation is an important condition for rural revitalization. The denser the road network is, the more convenient the transportation in the area is, and the more likely the villages in the area are to become model villages. Road construction is an important measure to improve traffic accessibility and is also a key project funded by local governments. Regional public road mileage reflects the investment and effectiveness of the local government in the construction of roads and has a significant impact on the spatial differentiation of model villages. In areas with high population density, the overall consumption capacity is strong, and the human capital stock is high, which is conducive to expanding the market for rural products and training of rural talent. Areas with many traditional villages have a long history of rural development and a profound cultural heritage. In the context of local rural revitalization policies that require the preservation and development of rural customs and culture, the distribution of traditional villages has a strong influence on the development of model village and its spatial differentiation.

The factors that have a strong impact on the spatial differentiation of the model villages in each province are the rural resident population and rural fiscal expenditure. Rural residents are the key subject of rural revitalization. For model villages distributed in areas with large rural population, the labor force is sufficient, and the rural revitalization can benefit more villagers. The government is another important stakeholder and primary driving force in promoting the construction of model villages and assists the construction of model villages through financial support and projects targeting the countryside. Therefore, the local government's financial support for the rural can largely affect the distribution of model villages. Factors such as topography, distances to level A scenic spots, and surrounding cities have weak explanatory power regarding the spatial differentiation of model villages in the YRD and various provinces.

5. Discussion

Amidst China's active promotion of rural revitalization and high-quality development, this paper took the YRD region, which has developed economy and significant regional heterogeneity, as an example and explored the geographic spatial differentiation characteristics of rural revitalization model villages in this region from multiple perspectives. Based on scientific analysis, this study offers a discussion on how to better promote the equilibrium distribution and sustainable development of rural revitalization model villages in China.

5.1. Implementing Rural Revitalization According to Local Conditions

At present, the rural revitalization model villages in the YRD exhibit disequilibrium and agglomeration spatial distribution, which is in line with the macro strategic requirement; that is, in the early implementation stage of the rural revitalization strategy, available resources should be concentrated to rapidly build templates for rural revitalization. After achieving the effective construction of model villages in typical regions, extending the experience of model village construction from one locality to a larger area has become an important goal for China as it seeks to accelerate rural revitalization and achieve common prosperity. However, it must be emphasized that, as a large country with a vast territory, in replicating and promoting the successful experience of model village construction in a larger area, China should deeply understand the differences in the rural development basis, resource conditions, and regional strategic orientation of different regions. Comparison of the driving factors regarding the spatial differentiation of rural revitalization model villages in the three provinces of Jiangsu, Zhejiang, and Anhui also shows this argument. Therefore, in the formulation and implementation of China's rural revitalization strategy in the future, it is necessary to not only take advantage of the spatial agglomeration characteristics of the model villages to strengthen their demonstration effect but also implement differentiated strategies based on different rural development realities, thus supporting the full realization of China's rural revitalization strategy by maximizing the resource utilization efficiency.

For the YRD region, there is a strong urgency to implement differentiated development orientation between the areas with densely distributed model villages and other regions. For areas with densely distributed model villages, i.e., areas along the Yangtze River, in central Zhejiang, in central Jiangsu, and in northern Anhui, it should focus on improving the overall quality of rural revitalization. On the one hand, relying on further improving the road networks, it is important to enhancing the interaction between the model villages with small geographical distances and similar development conditions to form rural revitalization demonstration zones which are spatially contiguous and have obvious overall demonstration effects. On the other hand, the demonstration zones should fully tap the supporting role of relevant policies, pay attention to innovating the ways of village environmental improvement and facility construction, and explore the path to integrate the primary, secondary, and tertiary industries to achieve balanced and high-quality development of the model villages. For areas with a relatively small number of model villages and relatively sparse distribution, the main task is to accelerate the process of rural revitalization. Resources such as funds, projects, and policies should be integrated to focus on supporting rural areas with high population density, suitable location, and transportation accessibility. Besides, it is necessary to promote rural development in a sequential manner from the construction of living environment, followed by industrial development and eventual rural revitalization. It is crucial to cultivate new business forms by taking full advantage of local resource endowment and historical and cultural connotations in these villages.

5.2. Multi-Subject Collaboration to Promote High-Quality Rural Development

In the socialist market economy with Chinese characteristics, the government plays an important role in promoting economic and social development and regulating the pattern of regional development. Many theoretical studies have shown that local government intervention not only has a significant impact on the creation of model villages and their spatial differentiation but also contributes to physical environmental improvement and socioeconomic regeneration of the rural areas. However, with the rigid constraints of limited financial resources, local government-led rural revitalization measures can only benefit a few villages directly; besides, they have the disadvantages of emphasizing the short-term construction and neglecting long-term operations and management [40]. For promoting both the sustainable development of established model villages and the construction of model villages from one locality to a larger area, the issue of cultivating endogenous development capacity of rural areas should be considered, which is a key objective of rural revitalization model village construction in China. The development of a cooperative governance model with community participation is the only way to transform from government-led model to farmers becoming practitioners and active promoters of rural revitalization.

Cooperative governance features the participation and collaborative governance of multiple stakeholders, which is underpinned by people-oriented governance concept, empowerment pathway, and win–win cooperation mechanism. To form a cooperative governance mode, all stakeholders should play their proper roles. The government should play its role as the guide of rural governance through macro policy formulation and the supply of basic resources, which includes mobilizing other actors to participate in rural development and supporting the reasonable demands of farmers while discouraging individual demands that affect the public interest of the countryside. Enterprises should play their role as supporters of rural governance including investing in rural construction and supporting industrial development to achieve mutual benefits with farmers through enhancing social responsibility and focusing on the long term benefits. Social elites should play the role of helpers, guides, and educators in rural governance, providing technical support for rural development and enhancing rural human capital. Villagers should become the key subject of rural construction and development, holding the responsibility of "building their own homes" and participating in rural public affairs actively. They need to realize self-empowerment with the support of government, enterprises, social elites, and other external forces and strive to improve their own skills and collective action, which will finally improve the endogenous development momentum of the village.

Promoting the development of collaborative governance in rural area is of great significance to improve the quality of rural revitalization. First, it helps to build a good communication framework and negotiation mechanism which can make the most of each stakeholder's role. Cooperative governance makes sure that different stakeholders participate in the decision-making process and make extensive consultation to obtain consensus on development. It enables rural governance to play the leading role of the government and obtain support from external forces, such as enterprises and social elites to achieve farmers' benefits. Second, it is beneficial to balance development among rural economy, society, and ecology. As the key subject of cooperative governance, villagers enhance their own awareness and abilities to participate through the educational and institutional empowerment by government and other entities. The empowerment also helps villagers to form a stronger sense of responsibility than foreign entities. Besides, the enhancement of human capital allows the emergence of farmer elites and their knowledge spillover is passed on, shared, and learned through rural social networks, which works in the long run to promote the overall labor productivity of villages [41]. The deep involvement of local villagers in the exploitation of local resources, socio-economic activities, and ecological conservation is beneficial to promote the sustainability of rural revitalization.

5.3. Supporting Rural Revitalization Strategy with Macro Policies Optimization

As China is a developing country, problems that arise in its development should be resolved in the course of development. Since the reform and opening up, actively playing the role of government has been a successful strategy in achieving the "growth miracle" of China's economy. However, in this process, the GDP-oriented political promotion championship has led the local government to formulate and implement a series of urban-biased development strategies, which have become the important factors in the accelerated decline in China's rural areas and the unbalanced development between urban and rural areas. It also has triggered the phenomenon that some rural areas copy the practices of urban development directly which exacerbates the pollution in the rural and affects the conservation of natural resources and the environment. As China's development shifts from high-speed growth to high-quality, there is a consensus that a certain economic growth rate should be sacrificed for the sake of development quality. In this context, promoting the reform of political performance evaluation at the institutional level and improving the institutional mechanism for urban and rural integrated development have become the foundations for accelerating rural revitalization. Meanwhile, exploring the path of rural ecological transformation to achieve the simultaneous growth of natural and economic "dual wealth" through policy guidance is the key to improving the quality of rural revitalization in the context of ecological civilization construction.

The central government, as the maker of China's macro policies, should firstly optimize the performance evaluation system to guide local governments to shift from focusing on the short-term performance of economic growth to long-term performance and from focusing on the growth rate to the development quality. By increasing the weight of coordinated urban and rural development in the performance appraisal, local governments must be forced to abandon the urban-biased strategy, curb the impulse to invest excessively in urban areas, and increase the proportion of fiscal support to the rural. It is also necessary to guide local governments to consider the resource endowment in the rural and villagers' initiative sufficiently, formulate goals and measures in line with long-term development, and avoid short-term and inefficient local economic growth. Secondly, the central government should improve institutional mechanisms and policy systems for the integrated development of urban and rural areas to promote the two-way flow of urban and rural elements. These include building an institutional framework for the free flow and equal exchange of urban and rural production factors, strengthening infrastructure construction for urban–rural coordination, establishing an integrated urban–rural public service system, completing the mechanism for linking and interest-sharing between enterprises and farmers, and strengthening policy support and financial subsidies.

In the process of ecological civilization construction, rural revitalization needs to fully consider the relationship among rural socioeconomic development, resource conservation, and environmental protection. The central government should encourage rural revitalization demonstration villages to explore the paths of ecological transformation, which will help to formulate goals and measures in line with rural resource protection and low environmental impact orientation. To promote rural ecological transformation, it is a prerequisite to strengthen awareness of ecological protection. Protecting and improving the ecological environment is the foundation while the formation of green production and eco-friendly way of life and the realization of the value of ecological products is the key. Therefore, the first thing to do is create a stronger awareness of sustainability in the policy, economic, and public spheres by publicity and education. Secondly, to play the key role of technology and knowledge in the ecological transformation, the government should increase support for the development of key technology of rural resource utilization and environment protection by policy support, financial subsidies, and establishing major research and development projects. In addition, the governments should help to build up a new production and consumption network between urban and rural areas to promote the rural ecological transformation by measures such as formulating subsidy policies for the development of ecological agriculture, accelerating the construction of a traceable quality certification system for ecological agricultural products, improving the pricing and market supervision mechanisms for ecological products, and guaranteeing the market outlets for ecological products.

5.4. Research Limitations

The results of this study are of great significance to the construction and sustainable development of rural revitalization model villages, but there is room for further in-depth research. First, due to the relatively short period for establishing model villages, this paper focused on the issue of spatial heterogeneity at specific time nodes and thus does not provide a comprehensive comparison of temporal and spatial heterogeneity. In the future, based on continuous attention to China's rural revitalization strategy and extensive collection of scientific data, more systematic quantitative indexes can be calculated, and conducting comparative analysis from multiple temporal and spatial perspectives will have great practical guiding significance. Second, rural revitalization involves multiple stakeholders, but given the limited availability of data and research scope, this paper focused mainly on the distribution pattern of model villages from the perspective of spatial heterogeneity, and the discussion about different interest groups related to model villages is insufficient. In the future, using a combination of qualitative and quantitative methods, under the premise of field investigation and comprehensive analysis of the interests of all parties and from the perspective of stakeholder interaction mechanisms, how to cultivate the endogenous dynamics of the rural areas to achieve rural revitalization and sustainable development can be studied, which represents an important research direction.

6. Conclusions

This study used the NNI, disequilibrium index, and KDE to analyze the spatial differentiation characteristics of rural revitalization model villages in the YRD and used the geographical detector method to reveal the driving factors. The main research conclusions are as follows: (1) The spatial distributions of rural revitalization model villages in the YRD and provinces all exhibited weak agglomeration characteristics and were imbalanced. Among the four regions of Shanghai, Jiangsu, Zhejiang, and Anhui, the imbalance in the spatial distribution of model villages in Anhui was the highest. (2) The distribution of rural revitalization model villages in the YRD was densest in areas along the Yangtze River and extending from the areas along the river to the northern and southern directions, the distribution was initially sparse and then dense. Model villages tend to agglomerate in places along rivers and lakes, close to traffic arteries and middle areas of the suburbs. (3) The spatial differentiation of rural revitalization model villages is the result of the combined effect of multiple factors, and the main driving factors are different under different spatial scales and in different regions. The most important driving factors for the spatial differentiation of the model villages in the YRD, Jiangsu, Zhejiang, and Anhui were the social development level and government intervention, transportation accessibility and economic development, resource endowment and natural conditions, transportation accessibility, and government intervention, respectively.

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Note

[1] Since some indexes are not available at the district level or are difficult to obtain, Shanghai is not included in the analysis of the influencing factors of each province.

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Article

Spatial Correlation and Influencing Factors of Tourism Eco-Efficiency in the Urban Agglomeration of the Yangtze River Delta Based on Social Network Analysis

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Abstract: Tourism eco-efficiency analysis is an effective tool to solve the problem of sustainable tourism development. The tourism eco-efficiency evaluation index system was constructed in the study, and the undesirable output super-slacks-based measure model was used to estimate the tourism eco-efficiency of 26 cities in the Yangtze River Delta. Then, the modified gravity model based on the values of the tourism eco-efficiency analysis of each city was used to construct a spatial correlation network. The structural characteristics of the spatial association networks of tourism eco-efficiency, the interrelationships among different cities, and the roles played by different blocks were explored using a social network analysis. The quadratic assignment procedure (QAP) was applied to analyze the influencing factors that affect the formation of the spatial association network of tourism eco-efficiency. The results show that tourism eco-efficiency has an overall increasing trend, and the gap among cities is decreasing. The structure of the spatial correlation network of tourism eco-efficiency has good connectivity, accessibility, and robustness with the correlations among all of the cities in the network. The spillover effects among the blocks are significant, showing spatial polarization, with the cities such as Shanghai, Suzhou, and Hangzhou occupying the core position of the network. The QAP analysis shows that the spatial correlation network of tourism eco-efficiency is affected by the distance between the cities and the levels of development of the economy and information dissemination. The results of this study innovatively reveal the structural characteristics and influencing factors of the spatial correlation network of tourism eco-efficiency. It could provide valuable insights for the development of corresponding policy measures by government sectors and tourism firms to enhance the sustainability of regional tourism development.

Keywords: undesirable output super-slacks-based measure model; spatiotemporal effects; quadratic assignment procedure; block models

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1. Introduction

Tourism eco-efficiency has a profound impact on the sustainable development of global tourism. The scale of human tourism activities is continuously increasing. The growth of tourism has significantly benefitted the tourism-receiving communities, economically, but it has also had many detrimental repercussions on the local environment, community, and culture. The negative effects of tourism on the environment have obvious cascading effects, making it difficult to remedy the "pollution first, then treatment" problem. This is due to the unique geographical conditions of the tourism areas and the relative concentration of tourist flow over time (tourist season) and space (tourist hotspots), resulting in a cycle of pollution that is caused by tourists. Therefore, the communities must seriously consider ways to make tourism sustainable over the long term to reap long-term economic and social advantages. Tourism depends on the environment for its existence and development, but it may also harm or even destroy it. Eco-efficiency seeks to strike a balance between environmental protection and economic gains, and its goal is to reduce the impact of the economic benefits on the environment to realize the harmonious development of local economic activities and ecological environment. Usually, the ratio of output-to-input is used to express eco-efficiency [1]. The value of the goods and services produced by a business or economic unit is referred to as its "output", and the consumption of its resource and energy and imposed environmental burden are referred to as its "input" [1]. An essential sign of sustainable tourism development is tourism eco-efficiency, which functions "on the basis of ensuring minimizing resource input and environmental damage and maximizing socioeconomic benefits as much as possible" [1]. The impact of the development of tourism in the current and long-term perspectives on the ecological environment [2] is based on the harmonious and balanced development of tourism resources and ecological environment [3] with the improvement of the quality of tourism development. In addition, the joint promotion of the regional linkage development strategy and the market mechanism has strengthened the spatial connection of tourism eco-efficiency. With the development of regional coordination and integration, the spatial relationship of tourism eco-efficiency presents a more complex network structure. Therefore, it is indispensable to further investigate tourism eco-efficiency and compare its spatiotemporal differences, spatial correlations, and influencing factors in different cities, and these are particularly essential for exploring the environmentally friendly and balanced development. The investigation of tourism eco-efficiency can provide new ideas for environmentally friendly eco-tourism and the sustainable development of urban industry. Tourism eco-efficiency plays a vital part in accelerating urban construction at the economic level, transforming and upgrading at the industrial level, and improving the development level of an urban agglomeration.

With the accelerated development of global tourism and the increased impacts of tourism activities on the environment, the eco-benefits of tourism are beginning to receive attention. For example, Gossling et al. analyzed the eco-efficiency of tourism in Seychelles and Amsterdam based on the carbon dioxide-equivalent emissions [4]. Kelly et al. explored the issue of optimizing eco-efficient tourism planning in tourist destinations from the tourist's perspective [5]. Becken used ten eco-efficiency indicators to measure the dependence of New Zealand's top ten international source markets on oil-based energy consumption [6]. Patterson et al. used the tourism satellite account and input–output tables to study the eco-efficiency of tourism in New Zealand [7]. The evaluation of tourism eco-efficiency usually includes both the economic income and the eco-environmental impact indicators [8–10]. Evaluations of tourism eco-efficiency have been performed more often on restaurants and accommodation businesses. For example, Li et al. used the bootstrap data envelopment analysis (DEA) to measure and calculate the eco-efficiency of the hotel industry in 31 provinces of China from 2016 to 2019 [11]. Xia et al. analyzed the spatial patterns of inputs and outputs and development trends of the eco-economic system of star-rated hotels in China based on the calculated levels of their economic efficiency and eco-efficiency in 30 provinces in China [12]. In previous studies, scholars have mainly applied the indicator system, a model analysis, and the economic–ecological single ratio methods to evaluate tourism eco-efficiency. For example, the measurement of tourism eco-efficiency in the economic–ecological single ratio method is expressed as the ratio of tourism revenue-to-environmental indicators such as the carbon emissions [3,13–15]. Recently, scholars have started to use more complex models to evaluate tourism eco-efficiency. These models mainly include the input–output methods [3], the DEA, and the stochastic frontier analysis [16]; of these, the DEA models are more widely used. For example, Li et al. used the super-slacks-based measure (SBM) DEA (SBM-DEA) with an undesirable output model to calculate the eco-efficiency values of provincial tourism in China [17]. Wang et al. constructed multiple regional tourism input–output index systems and calculated the tourism input–output ratios of 31 provinces in China from 1997 to 2016 using the undesirable output model in a DEA. Li et al. analyzed the spatial autocorrelation of the ecological efficiency of 28 national forest parks using the undesirable output super-SBM model of a DEA [18,19].

In general, the previous studies on tourism eco-efficiency have mainly focused on concept definition [20], model construction [5], efficiency measurement [4,21], and the influencing factors, and the formation mechanism [2,5]. However, previous studies have not addressed two aspects. Firstly, the previous studies were performed at the national [22], provincial [23,24], watershed [25], prefecture-level city [26,27], and tourist scenic area [28] scales. In these studies, tourism eco-efficiency was largely assessed based on individual spaces even though some of them confirm that the tourism eco-efficiencies of different regions are interdependent with some spatial correlation [29,30]. In addition, most of the existing literature adopts traditional spatial measures. These studies often limit the spatial correlation to geographically adjacent or similar regions [17–19,31], and they fail to explore the structural characteristics and driving factors of the spatial correlation of tourism eco-efficiency as a whole. Secondly, most of the existing literature is based on an "attribute data" analysis [16], and they can reflect only on the current situation of tourism eco-efficiency in each region without revealing the structural characteristics of the spatial linkages of the network of tourism eco-efficiency. Some studies have analyzed the structural characteristics of the spatial linkages of tourism eco-efficiency of the complete network from the perspective of "relationships". A social network analysis is an interdisciplinary and cross-domain research method based on relational data, and it is a new research paradigm in the fields of sociology, management, and economics [32,33]. However, few scholars have applied a social network analysis to study the spatial correlation of tourism eco-efficiency. This study uses the undesirable output super-SBM model to calculate the tourism eco-efficiency of 26 cities in the Yangtze River Delta region by constructing the tourism eco-efficiency index system. The spatial correlation network of eco-efficiency of inter-city tourism was constructed using the modified gravity model. Furthermore, the structural characteristics and influencing factors of the spatial correlation network of tourism eco-efficiency were analyzed using the social network analysis method.

The research questions that are posed in this study are as follows:

1. Are there spatial differences in the tourism eco-efficiency in different cities?
2. What is the spatial distribution pattern and evolutionary trend of tourism eco-efficiency?
3. What are the roles of different cities in the spatial correlation network of tourism eco-efficiency, and do they form different blocks?
4. What are the internal and external receiving or sending relationships of each block?
5. What factors, if any, have a significant impact on the formation of the spatial correlation network of tourism eco-efficiency?

From a practical point of view, it is very important to understand the spatial correlation of tourism eco-efficiency. The main suppliers of the cities with different tourism eco-efficiency values should include the government and tourism enterprises in the Yangtze River Delta. The government plays a leading role in the interaction of cities with different tourism eco-efficiency. Through the formulation of regional tourism cooperation plans, the government will make an overall allocation of capital, labor, energy, tourism resources, tourism services, and other aspects within the different cities. In response, tourism enterprises jointly design tourism routes, carry out publicity and promotional activities, provide reception services, and conduct other measures. This encourages the cities with different tourism eco-efficiencies to interact spatially. That is, the input behavior of the government and tourism enterprises forms the spatial correlation of tourism eco-efficiency. Therefore, the five questions above can provide valuable insights for the development of corresponding policy measures by government sectors and tourism firms to enhance the sustainability of regional tourism development. Four sub-goals were established to answer these questions. Firstly, the evaluation index system of tourism eco-efficiency was constructed from the aspects of input and output. The tourism inputs include five indicators of capital, labor, tourism resources, tourism services, and energy. The tourism outputs include the desirable and undesirable outputs. Secondly, the undesirable output super-SBM model was applied to measure the tourism eco-efficiency values of the different cities in the Yangtze River Delta, and their spatial differences and evolution patterns were analyzed. Thirdly, using the modified gravity model, the value of tourism eco-efficiency was transformed into the spatial correlation network of inter-city tourism eco-efficiency. This study used the social network analysis method to explore the structural characteristics of the spatial correlation network of tourism eco-efficiency, the relationships between the different cities, and the roles of the different functional segments. Fourthly, the quadratic assignment procedure (QAP) was applied to analyze the influencing factors that can affect the formation of the spatial association network of tourism eco-efficiency.

2. Materials and Methods

2.1. Study Area

The Yangtze River Delta is the junction area of the Belt and Road Initiative and the economic belt along the Yangtze River Basin, which plays a vital role in China's national modernization and opening-up program. According to the "Yangtze River Delta Development Plan" released by the General Office of the State Council in 2016, the Yangtze River Delta urban agglomeration consists of Nanjing, Changzhou, Shanghai, Wuxi, Suzhou, Nantong, Yancheng, Yangzhou, Zhenjiang, and Taizhou in Jiangsu Province, Hangzhou, Jiaxing, Ningbo, Huzhou, Shaoxing, Jinhua, Zhoushan, and Taizhou in Zhejiang Province, and Hefei, Ma'anshan, Wuhu, Chuzhou, Tongling, Anqing, Chizhou, and Xuancheng in Anhui Province. These 26 cities are a constant source of economic growth for China. In 2019, the tourism industry in the Yangtze River Delta was in a good condition. In Shanghai, Zhejiang, Jiangsu, and Anhui, the total number of tourist visits and the total revenue of tourism increased rapidly. The four provinces and cities in the Yangtze River Delta region received more than 370 million tourists, and the total number of tourists reached 2.811 billion, which is going up by 8.43% year-on-year, accounting for 32.62% of the total number of tourists in China. The total tourist income was CNY 3.91 trillion, which is going up by 12.3% year-on-year, accounting for 36.63% of the total tourist income in China. Analyses of the spatiotemporal evolution characteristics and dynamical mechanisms of tourism eco-efficiencies of these cities can provide valuable inputs for the sustainable development of tourism in cities of other regions and countries.

2.2. Construction of Tourism Eco-Efficiency Index System

This study constructed the tourism eco-efficiency evaluation index system based on previous studies combined with the available data for the cities in the Yangtze River Delta using the input and output variables (Table 1).

Table 1. Tourism eco-efficiency evaluation index.

Indicator Type	Indicator Name	Primary Parameter	References
Input	Capital input	Investment in fixed assets for tourism	Lu et al. [8]; Yang et al. [9]; Wang et al. [10]; Wang et al. [29]; Chaabouni [31]; Wang [34]; Hu [35].
	Labor input	Number of tourism employees	Lu et al. [8]; Yang et al. [9]; Wang et al. [10]; Chaabouni [31]; Wang [34]; Hu [35].
	Tourism resource	Number of A-level scenic spots	Lu et al. [8]; Yang et al. [9]; Wang et al. [29]; Wang [34]; Hu [35].
	Tourism service	Number of star hotels	Yang et al. [9]; Wang et al. [29]; Wang [34]; Hu [35].
		Number of travel agencies	Wang et al. [29]; Wang [34]; Hu [35].
	Energy input	Water supply	Peng et al. [27]; Guo et al. [36].
		Power supply	Peng et al. [27]; Guo et al. [36].
Desirable Output	Total tourism economy	Total tourism revenue	Lu et al. [8]; Yang et al. [9]; Wang et al. [10]; Chaabouni [31]; Wang [34]; Hu [35].
		Visitor reception volume	Lu et al. [8]; Yang et al. [9]; Wang et al. [10]; Chaabouni [31]; Wang [34].
Undesirable Output	Tourism environmental pollution	Wastewater discharge from tourism	Lu et al. [8]; Yang et al. [9]; Wang et al. [10].
		SO_2 emissions from tourism	Lu et al. [8]; Yang et al. [9]; Wang et al. [10].
		Smoke emissions from tourism	Yang et al. [9].

2.3. Methods

2.3.1. Undesirable Output Super-SBM Model

The undesirable output super-SBM model proposed by Tone is an improvement on the conventional DEA model as it corrects the bias developed because of the radial and directional problems and accurately assesses the relationship between the inputs and outputs [37]. This study used this model to gauge the tourism eco-efficiency [37]. The formulas used are as follows:

$$\rho = \min \frac{1 + \frac{1}{m}\Sigma_{i=1}^{m}\frac{s_i^x}{x_{i0}}}{1 - \frac{1}{s_1+s_2}\left(\Sigma_{k=1}^{s_1}\frac{s_k^y}{y_{k0}} + \Sigma_{l=1}^{s_2}\frac{s_l^z}{z_{l0}}\right)} \tag{1}$$

$$\text{s.t. } x_{i0} \geq \Sigma_{j=1,\neq 0}^{n}\lambda_j x_j - s_i^x, \forall i \tag{2}$$

$$y_{k0} \leq \Sigma_{j=1,\neq 0}^{n}\lambda_j y_j - s_k^y, \forall k \tag{3}$$

$$z_{l0} \leq \Sigma_{j=1,\neq 0}^{n}\lambda_j z_j - s_l^z, \forall l \tag{4}$$

$$1 - \frac{1}{s_1+s_2}\left(\Sigma_{k=1}^{s_1}\frac{s_k^y}{y_{k0}} + \Sigma_{l=1}^{s_2}\frac{s_l^z}{z_{l0}}\right) > 0 \tag{5}$$

$$s_i^x \geq 0, s_j^y \geq 0, s_l^z \geq 0, \lambda_j \geq 0, \forall i, j, k, l \tag{6}$$

where ρ indicates the tourism eco-efficiency value; m, s_1, and s_2 represent the number of variables of input, the desirable output, and the undesirable output, respectively; x_{i0}, y_{k0}, and z_{l0} are the elements in the corresponding input, desirable output, and undesirable output matrices, respectively; λ is the weight vector. Here, s^x, s^y, and s^z are not slack variables in the traditional sense, but they are slack variables indicating the inputs, the desirable outputs, and the undesirable outputs, respectively.

2.3.2. Modification of the Gravity Model

Gravity is a law of nature that was originally published by Isaac Newton in 1687 in his work 'Mathematical Principles of Natural Philosophy'. The law of gravity was later applied to the field of economics. Economists believe that there is a law of economic linkage between regions which is similar to gravity, i.e., the strength of the linkage between regions is proportional to the "mass" of the regions; the strength of the linkage between regions is inversely proportional to the "distance" between the regions, as influenced by the law of decay of distance [38]. Since Zipf first applied the modified gravitational model to the analysis of inter-city connections in 1942, the gravitational model has been widely used in the study of regional spatial interconnection [39–41]. Therefore, the interrelationships of tourism eco-efficiency of the different cities in Yangtze River Delta can be investigated using the modified gravitational model according to the following equations:

$$F_{ij} = K_{ij}\frac{E_i \cdot E_j}{D_{ij}^2} \tag{7}$$

$$K_{ij} = \frac{E_i}{E_i + E_j} \tag{8}$$

$$D_{ij}^2 = \left(\frac{d_{ij}}{g_i - g_j}\right)^2 \tag{9}$$

where *Fij* is the intensity of the tourism eco-efficiency linkage of each city; *Kij* is the gravitational coefficient; *Ei* and *Ej* represent the tourism eco-efficiency of city *i* and city *j*, respectively; *Dij* indicates the "economic distance" between city *i* and city *j*; *dij* is the spherical distance between the cities; *gi* and *gj* represent the GDPs of city *i* and city *j*, respectively [40]. The spatial correlation matrix of tourism eco-efficiency is structured by the gravity model, and the mean value of each row of data in the matrix is used as the threshold for then binarization. If *Fij* is greater than the mean value, then it takes the value of 1, which means that there is a spatial correlation between the cities in terms of tourism eco-efficiency, and vice versa, if it takes the value of 0, that means that there is no spatial correlation.

2.3.3. Social Network Analysis

Based on the gravity model, this study calculated the spatial correlation of tourism eco-efficiency in the Yangtze River Delta urban agglomeration and constructed the relationship matrix, which was further binarized. Then, Ucinet 6.0 software was used to analyze the social network of the processed matrix.

(1) Characteristics of the whole network

The overall network characteristics are mainly measured by their density, connectedness, hierarchy, and efficiency, reflecting the spatial association network's strength of association and structure of tourism eco-efficiency (Table 2). The network density is expressed as the ratio of the actual number of tourism eco-efficiency relationships between the cities in the network to the theoretical maximum number of relationships. Network connectedness measures the degree of connectedness in the tourism eco-efficiency spatial network. The network hierarchy measures the quantum of asymmetric accessibility that exists between the cities in the tourism eco-efficiency spatial network. Network efficiency measures the efficiency of connectivity between the cities in the tourism eco-efficiency spatial network.

Table 2. Formulas for the structural characteristics of spatial correlation network of tourism eco-efficiency.

Indicator Type	Indicator Name	Formula	Meaning of Variables
Characteristics of the whole network	Network density (*ND*)	$ND = a/[b(b-1)/2]$	a is the number of cities
	Network connectedness (*NC*)	$NC = 1 - V/[b(b-1)/2]$	V is the number of "0s" on the diagonal of the reachable matrix
	Network hierarchy (*NH*)	$NH = 1–S/max(S)$	S stands for the logarithms of symmetric nodes in spatially associated networks
	Network efficiency (*NE*)	$NE = 1–K/max(K)$	K is the actual number of redundant relationships in the spatial association network structure
Characteristics of the individual network	Degree of centrality (*DC*)	$DC = d/(b-1)$	d is the number of direct relationships between a city and other cities in a spatial association network
	Closeness centrality (*CC*)	$CC = \sum_{j=1}^{b} l_{ij}$	l_{ij} distance, namely in the shortcut contains the number of relations
	Betweenness centrality (*BC*)	$BC = \frac{2\sum_p^b \sum_q^b n_{pq}(i)}{b^2-3b+2}$ $n_{pq}(i) = g_{pq}(i)/g_{pq}$	g_{pq} is the number of the shortcuts between the node p and the node q; $g_{pq}(i)$ is the number of the node p and node q after the node i; $n_{pq}(i)$ means the probability that node i is in the number of shortcuts between nodes p and q; $p \neq q \neq i,\ p < q$

(2) Characteristics of the individual network

The characteristics of an individual network mainly describe the position and role of each city in the spatial correlation network of tourism eco-efficiency through centrality, and the measurement indicators are the degree, closeness, and betweenness of the centrality. The degree of centrality measures the centrality of each city in the spatial correlation network of tourism eco-efficiency according to the number of connections. Closeness centrality is the degree to which a city is directly related to other cities in the spatial network of tourism eco-efficiency. Betweenness centrality measures the extent to which a city is in the "middle" of the tourism eco-efficiency transmission path of other cities.

2.3.4. Quadratic Assignment Procedure (QAP)

In this study, a QAP analysis was applied to analyze the driving factors of the spatial correlation network of tourism eco-efficiency. The QAP is an arrangement based on the matrix data, and it can compare the similarity of individual cells in two or more matrices. That is, the single cell of the matrix is compared, and the correlation coefficient between the two matrices is given. Then, the coefficient is non-parametrically tested. The individual observations of the relational data are not independent of each other. Parameter estimation and statistical tests cannot be performed with many standard statistical procedures (e.g., ordinary least squares regression) because the observation terms are not independent of each other, and incorrect standard deviations are calculated. Therefore, scholars use a randomization test (e.g., randomly controlled trial) method that is termed QAP, which is a resampling-based method that excludes the spurious structural relationships. The QAP is commonly applied in tourism, sociology, and geography studies [38,39]. The QAP can analyze the driving factors of tourism eco-efficiency development based on no pseudo-structure relationship, therefore, it better reflects the interrelationships between the cities compared to other regression analysis methods, and it provides more realistic, reliable, and specific insights for improvement, thereby enabling the sustainable development of tourism in the long run.

This study constructs the evaluation model of driving factors of the spatial correlation network of tourism eco-efficiency:

$$R = f\,(EDL, TIS, TIL, TRE, DBC, IDL) \tag{10}$$

where R is the tourism eco-efficiency network relationship matrix, Economic development level (EDL) denotes the difference matrices of the Economic development level, Tourism investment level (TIL) denotes the difference matrices of the tourism industry status, Tourism investment level (TIL) denotes the difference matrices of the Tourism investment level, Tourism resource endowment (TRE) denotes the difference matrices of the Tourism resource endowment, Distance between cities (DBC) denotes the difference matrices of the Distance between cities, and Information development level (IDL) is the difference matrices of the Information development level.

EDL: The EDL of a city has a vital contribution to the development of tourism ecological resources, the construction of infrastructure, and the betterment of the ecological environment in which the tourism occurs. Cities with a high EDL invest more in tourism development with relatively well-developed attractions and infrastructure and a relatively efficient flow of tourism production resources, indicating the good connectivity of tourism eco-efficiency between the cities. Therefore, the EDL is a vital factor that affects the spatial correlation network.

TIS: The TIS reflects the government's intention and goal to achieve regional economic development based on tourism. The more the government pays attention to the development of the tourism industry, the more importance it attaches to it, and the more helpful it is to improve the eco-efficiency of tourism. Therefore, the TIS will affect the spatial correlation network.

TIL: The higher the capital injection is, the more guarantee that there will be a quality of the tourism elements. The TIL also promotes more frequent inter-city communication in the tourism industry, thus promoting inter-city cooperation in tourism production, and finally, it has an impact on the spatial correlation network.

TRE: The TRE can be used as the primary attraction of the development of the tourism industry in each city. Therefore, the TRE is an important factor that affects the spatial correlation network.

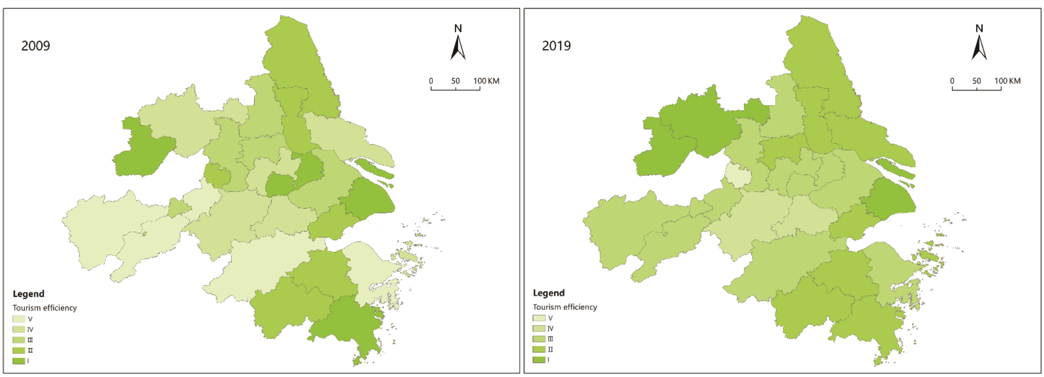
DBC: The farther the DBC is, the more it will affect the transportation and information transfer efficiencies of the tourism elements between the cities, which in turn will affect the spatial correlation network.

IDL: The higher the IDL is, then the more convenient the flow of the tourism production factors are. Therefore, it is an influencing factor of the spatial correlation network.

3. Results and Discussion

3.1. Spatial Differences in Tourism Eco-Efficiency in Different Cities

There are spatial differences in tourism eco-efficiency in different cities. The natural breaks (Jenks) method in ArcGIS 10.5 software was used to grade data in 2009 and 2019. The data were classified into grades I, II, III, IV, and V according to the color from dark to light (Figure 1). Through a comparative analysis, the spatial differentiation and dynamic change patterns of tourism eco-efficiency were revealed. In previous studies, some scholars have adopted similar classification methods, but they generally focus on the spatial differences of urban tourism eco-efficiency in countries and provinces [18,42–45].



(**a**) (**b**)

Figure 1. Evolution of spatial differences in tourism eco-efficiency in (**a**) 2009 and (**b**) 2019.

Firstly, the mean value of tourism eco-efficiency increased from 0.9788 in 2009 to 1.1167 in 2019, with an average annual growth rate of 1.28%. In general, the mean value of tourism eco-efficiency shows an increasing trend probably because of the implementation of tourism energy conservation and emission reduction projects in these cities, which reduce the impact of the tourism economic activities on the ecological environment and promote the continuous development of the ecological civilization. This conclusion is different from that of Sun et al. Sun et al. believed that during the study period, the tourism eco-efficiency in the Yangtze River Delta showed a fluctuating trend of it first declining, then rising, and then declining [16]. The reason for this is that the index selection of the tourism eco-efficiency measurement that was conducted by Sun et al. was not as comprehensive as it is in this study, and the measurement method is also different from this study.

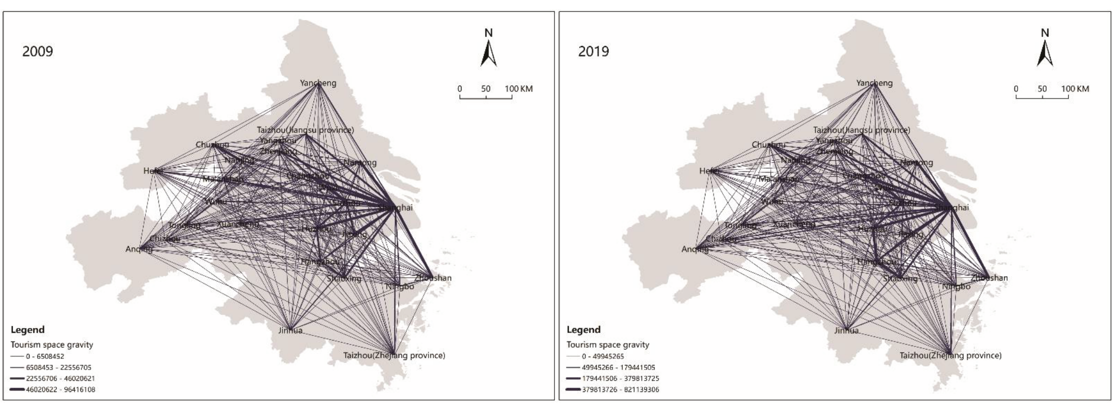
Secondly, the spatial distribution of tourism eco-efficiency is uneven. The number of cities in ranks II and III contribute to 76.9% of the total number of cities, which indicates that the tourism eco-efficiencies of most of the cities are at a medium-to-high level. In 2019, Shanghai, Chuzhou, and Hefei were classified as grade I cities. Yancheng, Taizhou (Jiangsu), Nantong, Zhenjiang, Shaoxing, Jinhua, Taizhou (Zhejiang), Jiaxing, and Zhoushan were grade II cities. Yangzhou, Nanjing, Changzhou, Wuxi, Suzhou, Anqing, Chizhou, Tongling, Ningbo, Hangzhou, and Wuhu were grade III cities. Huzhou and Xuancheng were grade IV cities. Only Ma'anshan was a grade V city. Again, the tourism eco-efficiency of some cities showed fluctuating trends. Among them, 10 cities showed an increasing trend, including Nantong (IV→II), Zhenjiang (III→II), Changzhou (IV→III), Chuzhou (IV→I), Anqing (V→III), Chizhou (V→III), Wuhu (V→III), Hangzhou (V→III), Ningbo (V→III), and Zhoushan (IV→II), which are probably due to the rapid growth of the tourism economy, which leads to the rapid improvement of tourism eco-efficiency.

Three cities showed a downward trend, namely Wuxi (I→III), Ma'anshan (I→V), and Wenzhou (I→II). Although these three cities also have a high TRE, the advantages of the tourism resources have not been transformed into advantages for the tourism economy because of the limitations of the unfavorable conditions such as the development of the economy, transportation, location, and science and technology. In addition, the balance between the tourism economic growth and carbon emission and energy consumption has been neglected, which finally leads to the continuous decline of tourism eco-efficiency.

3.2. Spatial Correlation Network Analysis of Tourism Eco-Efficiency

3.2.1. Analysis of the Whole Network

Based on the modified gravity model, the spatial correlation matrix of the tourism eco-efficiency of 26 cities was calculated. ArcGIS 10.5 and UCINET 6.0 software were used to construct the spatial correlation network of tourism eco-efficiency in 2009 and 2019 (Figure 2). This is significantly different from the previous spatial analysis based only on the "attribute data" [16]. Based on the "relational data" (spatial correlation matrix), this study further uses the social network analysis to reveal the structural characteristics of the spatial linkages of tourism eco-efficiency network, which is also well applied to the existing research [46]. Based on the analysis of the spatial difference in tourism eco-efficiency in the Yangtze River Delta urban agglomeration, this study combined the analysis of SNA and GIS to construct the spatial correlation network of tourism eco-efficiency in the Yangtze River Delta urban agglomeration. Figure 2 shows that the tourism eco-efficiencies of the 26 cities do not exist in isolation, and they have obvious gravity (correlation) in space. The gravity (correlation) between the cities gradually increased from 2009 to 2019. Previous studies have pointed out that the cities with different tourism eco-efficiency values have the characteristics of cluster and spatial spillover effects [17]. This study is a further exploration of its spatial correlation, and the conclusion is also a validation of its spatial correlation.



(**a**) (**b**)

Figure 2. Spatial correlation network of tourism eco-efficiency in (**a**) 2009 and (**b**) 2019.

The degree of network correlation was used to measure the closeness of the connections between the different city nodes in the spatial correlation network. From 2009 to 2019, the network connectivity of the spatial correlation network of tourism eco-efficiency in 26 cities was one, indicating that all the cities were connected. The spatial correlation network structure performed well in terms of its connectivity, accessibility, and robustness (Figure 3).

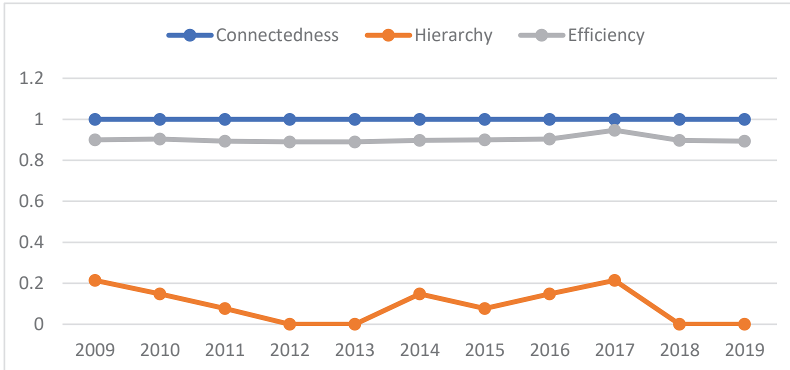


Figure 3. Relevance, hierarchy, and efficiency of the tourism eco-efficiency network.

From 2009 to 2019, the hierarchical average of the spatial association network of tourism eco-efficiency was 0.214, which is in the middle and lower levels, and shows a downward trend, indicating that the differences in the tourism eco-efficiencies between the cities are decreasing, and more core nodes of the network have emerged. The network level for 2012, 2013, 2018, and 2019 was 0, indicating that each node has a high possibility of having a spatial spillover effect. On the other hand, the network efficiency was applied to measure the relationships in the spatially connected network. The higher the network efficiency, the more spatial correlations indicated. From 2009 to 2019, the network efficiency of the spatial correlation network was approximately 0.9, which was at a high level, indicating that the network has high correlation and redundancy. These conclusions are consistent with the conclusion of Wang [41].

3.2.2. Analysis of Individual Network Characteristics

UCINET 6.0 software was used to analyze the centrality of the spatial correlation network of tourism eco-efficiency. The degree of centrality is the number of other cities that are directly connected to a city. A high value of the degree of centrality indicates that the city has a high number of connections to other cities. The point-out and point-in degrees characterize the number of relationships that are sent from the city to other cities and the number of relationships received from other cities, respectively. The mean value of the degree of centrality of tourism eco-efficiency was approximately 17. The degree of centrality of Shanghai, Suzhou, Nanjing, and Hangzhou were above the average, indicating that these cities have a high spatial correlation and priority in the tourism eco-efficiency correlation network. The point-out degrees of 26 cities were >0, indicating that the tourism eco-efficiencies of each city have some spatial radiation. Shanghai, Suzhou, Nanjing, and Hangzhou have higher than average point-out degrees, while Yancheng, Taizhou (Zhejiang), Ma'anshan, Anqing, and Chizhou have a smaller number of relationships. In terms of the point-in degree, Shanghai also has the highest number of receiving relationships, up to twenty-four, while Yancheng, Taizhou (Zhejiang Province), and Anqing have the lowest number of receiving relationships with only one.

Closeness centrality considers the average length of the shortest route from each city to the other cities (Table 3). The larger that its value is, then the closer it is to other cities. The closeness centrality of the city ranges from 51 to 100, indicating that each city in the spatial correlation network can be connected with the other cities relatively quickly. The closeness centrality of Shanghai, Nanjing, Suzhou, and Hangzhou were higher than the average value of 54.53, indicating that these cities play the role of "core actors" in the spatial correlation network and they can lead its development, probably because these cities are not only geographically superior, but they are also able to effectively develop and utilize tourism resources such that the economic benefits of tourism are guaranteed. The values of closeness centrality of

22 cities, such as Changzhou, Ningbo, and Wuhu, were lower than the average value of 54.53, indicating that the eco-efficiency of tourism is relatively low, and hence, they are restricted as the other cities make them passive in the spatial correlation network.

Table 3. Centrality analysis of the spatial correlation network of tourism eco-efficiency in 2019.

City	Degree			Closeness	Betweenness	City	Degree			Degree	Degree
	Out	In	Center				Out	In	Center		
Shanghai	25	24	100	100.00	72.21	Huzhou	4	4	16	54.35	0.22
Nanjing	8	7	32	59.52	2.56	Shaoxing	3	3	12	53.19	0.06
Wuxi	4	3	16	54.35	0.11	Jinhua	2	2	8	52.08	0.00
Changzhou	2	3	12	53.19	0.00	Zhoushan	4	4	16	54.35	0.39
Suzhou	13	14	56	69.44	11.11	Taizhou (Zhejiang)	1	1	4	51.02	0.00
Nantong	2	2	8	52.08	0.00	Hefei	3	2	12	53.19	0.17
Yancheng	1	1	4	51.02	0.00	Wuhu	3	3	12	53.19	0.05
Yangzhou	4	4	16	54.35	0.05	Ma'anshan	1	2	8	52.08	0.00
Zhenjiang	4	4	16	54.35	0.05	Tongling	2	2	8	52.08	0.00
Taizhou (Jiangsu)	3	3	12	53.19	0.05	Anqing	1	1	4	51.02	0.00
Hangzhou	7	7	28	58.14	1.94	Chuzhou	3	2	12	53.19	0.05
Ningbo	2	2	8	52.08	0.00	Chizhou	1	2	8	52.08	0.00
Jiaxing	3	3	12	53.19	0.06	Xuancheng	3	4	16	54.35	0.27

Betweenness centrality reflects the number of bridges that serve as the shortest way to the other two cities (Table 3). The higher the value is, then the more control it has in the network. Shanghai, Nanjing, and Suzhou play a significant mediating role in the spatial correlation network. The sum of the betweenness centrality values of these three cities account for 96% of the total, indicating that they play the role of key nodes in the spatial correlation network, and they can connect various cities and perform well in the transfer process of the tourism production factors and the tourism resources. Similarly, these cities also have a strong ability to control the network.

Shanghai, Suzhou, and Nanjing also have significant characteristics in the aspect of the individual network characteristics. The tourism eco-efficiency of these three cities can be quickly connected with the other cities, and they play the role of "core actors" and play the roles of being a "bridge" and an "intermediary", which is consistent with the conclusion of Wang [41].

3.3. Block Model Analysis

In this study, the convergence of the iterated correlations (CONCOR) algorithm in UCINET 6.0 software was used to classify 26 cities into four blocks by selecting two as the maximum segmentation depth and 0.2 as the convergence criterion (Figure 4) [39]. By compared it with the spatial error model (SEM) that has been used by previous scholars to analyze the spatial spillover effect [17], the block model analysis studies the spillover relationship between the blocks, which can more intuitively understand the flow of tourism-related resources between the blocks and the relationships within and between the blocks. The spatial correlation of tourism eco-efficiency of 26 cities in 2019 was further analyzed using the block model. Block I includes Shanghai, Suzhou, and Hangzhou. Block II includes Tongling, Anqing, Hefei, Yancheng, Nanjing, Ningbo, Chizhou, and Taizhou (Zhejiang). Block III includes Huzhou, Changzhou, Xuancheng, Wuxi, Jinhua, Zhoushan, Shaoxing, Jiaxing, and Nantong. Block IV includes Yangzhou, Ma'anshan, Taizhou (Jiangsu), Chuzhou, Zhenjiang, and Wuhu. Table 4 shows 218 spatial network relationships of tourism eco-efficiency in 2019. There are 24 intra-block relationships, accounting for 11% of the total number of relationships. One hundred and ninety-four relationships were between the blocks, accounting for 89% of the total, indicating that the intra-block aggregation effect is relatively weak, while the inter-block spatial correlation is relatively significant. The spatial spillover effect plays a leading role in the spatial correlation network structure of tourism eco-efficiency. Furthermore, this study compares the internal and external correlations of each block and the ratio of the expected internal relationship to the actual internal relationship. The results show that Shanghai, Suzhou, and Hangzhou in block I are the "core actors" in the spatial correlation network of tourism eco-efficiency probably due to their strong tourism economic strength, obvious location advantages, and high tourism eco-efficiency level which easily attract the inflow of socioeconomic and environmental resources and other factors from other cities. However, due to their relatively backward economic foundation, their remote geographical location, and their low development level of tourism eco-efficiency, the cities in the other three blocks are highly dependent on the cities in block I. Therefore, the spillover effect of block I is very significant.

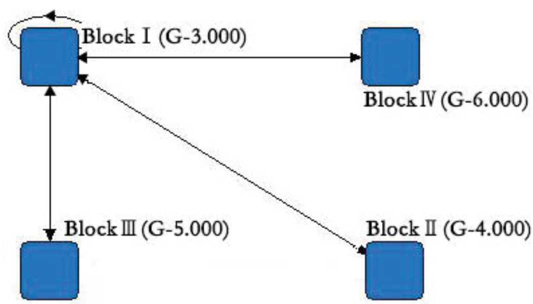


Figure 4. Diagram of block model analysis for 2019.

Table 4. Spillover effects of tourism eco-efficiency spatially related blocks in 2019.

	Receiving Relationship Matrix				Number of Members	Number of Receiving Relationships		Number of Sending Relationships		Desired Internal Relationship Ratio	Actual Internal Relationship Ratio	Characteristics
	Block I	**Block II**	**Block III**	**Block IV**		**In**	**Out**	**In**	**Out**			
Block I	4	8	23	10	3	4	41	4	41	8%	9%	Core actors
Block II	8	3	1	6	8	3	15	3	16	28%	16%	Marginal actors
Block III	23	2	3	0	9	3	25	3	24	32%	11%	Marginal actors
Block IV	10	6	0	2	6	2	16	2	16	20%	11%	Marginal actors

The network density matrix of the block was calculated based on the results in Table 4. The network density matrix was transformed into the image matrix using some criteria (Table 5). Figure 4 shows the significant centralization trend of the 26 cities, and the block model structure in 2019 is a typical "core-edge structure". All of the relationships in the spatial correlation network of tourism eco-efficiency are from block I. Only block I has a value of one on the diagonal of the homogeneous matrix, indicating that block I has a reflexive relationship, that is that it can supply to other cities well, while satisfying itself, and its internal tourism eco-efficiency has a more significant correlation. There is a bidirectional spillover relationship between block I and the other three blocks; however, the spillover relationships among blocks II, III, and IV are not significant.

In terms of the overall spatial distribution pattern, the spillover of block I, which is the core of the spatial correlation network, is the most obvious. Block III has the second highest number of spillover relationships, which mainly spillover to block I. Blocks II and IV have the same number of spillover relationships. Blocks II and IV are at the outermost parts of the entire network, confirming that the average network density in the whole network is at a moderate-to-low level, and the network is relatively loose. This also confirms the "low network hierarchy" conclusion that is mentioned above, where the members of the blocks are only classified into "core actors" and "fringe actors". The spatial variation of tourism eco-efficiency combined with the conclusion of this study indicates that the tourism eco-efficiencies of Shanghai, Suzhou, and Hangzhou are more fragmented, and this narrows the gap in the tourism eco-efficiency within the region, and the Matthew effect is sufficiently mitigated to be more beneficial to the tourism eco-efficiency of the overall network.

Table 5. Density and image matrixes of spatially related blocks of tourism eco-efficiency.

	Density Matrix					Image Matrix			
	Block I	**Block II**	**Block III**	**Block IV**		**Block I**	**Block II**	**Block III**	**Block IV**
Block I	0.667	0.333	0.852	0.556	Block I	1	1	1	1
Block II	0.333	0.054	0.028	0.125	Block II	1	0	0	0
Block III	0.852	0.014	0.042	0.000	Block III	1	0	0	0
Block IV	0.556	0.125	0.000	0.067	Block IV	1	0	0	0

3.4. Influencing Factors

3.4.1. Selection of Influencing Factors

The occurrence and development of the spatial correlation network of tourism eco-efficiency is a direct reflection of the interaction and cooperation of the resource elements in the tourism geographical spaces of 26 cities. The resultant force formed by different influencing factors in the interrelation leads to the realization of this process. The change in resultant force strength [40] affects the degree of development of the structure of the spatial correlation network.

The EDL directly affects the cooperation of tourism projects between the cities, and then, affects the development level of the spatial correlation network structure of tourism eco-efficiency. Therefore, gross domestic product (GDP) was used in this study to represent the level of regional economic development [41].

The status of the tourism industry can reflect the government's emphasis on regional tourism development and the ability for the regional tourism factors to agglomerate. The higher the development level of the tourism industry is, then the wider the flow space of the regional tourism production factors is. Therefore, this study selected the total income from tourism as a proportion of the GDP to represent the status of the tourism industry [47].

Capital radiates and diffuses into the frontier regions through various media, which improve the quality and efficiency of regional tourism, and it is measured by the investment in fixed assets for tourism [40]. The TRE influences the flow and configuration of the tourism input factors among the provinces and municipalities, thus influencing the division of labor and cooperation of their tourism industries as determined by the total number of scenic spots at different levels [48].

Gravity is inversely proportional to the square of the distance, and the path dependence can be regarded as the inertia. The closer the distance between the two cities is, then the more favorable the spillover of tourism eco-efficiency is. The spillover between the cities is more likely to follow the existing path (inertia), which is represented by the spherical DBC [49]. The IDL is an important pathway of spatial agglomeration and the radiation of tourism economy between the cities, and it is expressed in terms of total postal and telecommunications services [50].

In this study, the spatial correlation matrix of tourism eco-efficiency of 26 cities in 2019 was selected to be the explained variable. The difference matrices of the EDL, the status of the tourism industry, the TIL, the TRE, the DBC, and the IDL were used as the explanatory variables in the QAP analysis (Table 6).

Table 6. Influencing factors for the construction of the index of the spatial correlation network of tourism eco-efficiency.

Indicator Name	Primary	Expectation	References
Economic development level	Gross Domestic Product	+	Liu et al. [22]; Wang et al. [51].
The status of the tourism industry	Total income from tourism accounts for the proportion of GDP	+	Liu et al. [22]; Hu et al. [35]; Wang et al. [51].
Tourism investment level	Investment in fixed assets for tourism	+	Wang et al. [38]; Wei et al. [40].
Tourism resources endowment	Total number of A-level scenic spots (spots)	+	Hu et al. [35]; Lu et al. [48].
Distance between cities	Spherical distance between cities	−	Wang et al. [38]; Liu [49].
Information development level	Total postal and telecommunications services	+	Wang et al. [38]; Chen [50].

3.4.2. Analysis of Influencing Factors

The driving factors have an important influence on the formation and evolution of the spatial correlation network of tourism eco-efficiency. Therefore, the QAP analysis is used to measure the influence of various driving factors on the nature, direction, and intensity of the spatial correlation of tourism eco-efficiency. The QAP is a method based on re-sampling, which can successfully eliminate the false structural relationship. This method has been very common in the research of tourism, sociology, and geography [38,39]. The QAP correlation and regression analyses were performed to outline the influencing factors of the spatial correlation network of tourism eco-efficiency in 26 cities. UCINET 6.0 software was used to conduct the QAP correlation analysis on the spatial correlation matrix and influencing factor matrix of tourism eco-efficiency. Five thousand random permutations were selected, and the correlation analysis results are shown in Table 7.

Table 7. Results of QAP correlation analysis.

Independent Variable	QAP Correlation Analysis	
	Correlation Index	*p* Value
Economic development level	0.585 ***	0.000
Status of the tourism industry	−0.039	0.398
Tourism investment level	−0.145 **	0.032
Tourism resources endowment	0.112	0.127
Distance between cities	−0.233 ***	0.000
Information development level	0.620 ***	0.000

Note: *** and ** indicate significance levels of 0.001 and 0.05, respectively.

The difference matrices of the EDL and the IDL are positively correlated with the spatial correlation network of tourism eco-efficiency. The correlation coefficient is positive and significant at the 1% level, which confirms the research hypothesis. This further indicates that the higher the EDL and IDL are, then the more conducive they are for to the formation and development of the spatial correlation network of tourism eco-efficiency.

The difference matrix of the DBC is negatively correlated with the spatial correlation network of tourism eco-efficiency. The correlation coefficient is positive and significant at the 1% level, which indicates that the closer the DBC is, then the more conducive it is for the formation and development of the spatial correlation network of tourism eco-efficiency. The cities with higher tourism eco-efficiencies will preferentially affect nearby the cities with lower tourism eco-efficiencies, and then, they will gradually promote the improvement of tourism eco-efficiency of the whole region.

The difference matrix of the TIL is negatively correlated with the development of the spatial correlation network of tourism eco-efficiency. The correlation coefficient is negative and significant at the 5% level, which is not consistent with the research hypothesis, indicating that tourism capital hinders the improvement of inter-city tourism eco-efficiency.

The correlation between the difference matrices of the TIS and the TRE and the spatial correlation network of tourism eco-efficiency were not strong, and both of them were not significant probably because the status of the tourism industry reflects the government's intention and goal to achieve regional economic development based on tourism. The TISs of the different cities are different, which is not conducive for the cooperation between the cities with low and high TIS values, and it further hinders the formation and development of the spatial correlation network of tourism eco-efficiency. Tourism resources are essential for the development of the tourism industry. Because of the similarity of the tourism resources in various cities, the competition among the cities is fierce, which hinders the formation and development of the spatial correlation network of tourism eco-efficiency.

Based on the correlation analysis, this study selected the matrices of difference of the EDL, the TIL, the DBC, and the IDL for the QAP regression analysis. The results of the QAP regression analysis are shown in Table 8. The adjusted $R^2 = 0.487$, which is significant at the 1% level, indicates that the four influencing factor matrices explain 48.7% of the spatial correlation of tourism eco-efficiency.

Table 8. Results of QAP regression analysis.

Independent Variable	QAP Regression Analysis		
	Unstandardized Coefficients	Standardized Coefficients	*p* Value
Economic development level	0.2537 ***	0.3241 ***	0.0005
Tourism investment level	0.0123	0.0159	0.3408
Distance between cities	−0.1626 ***	−0.2176 ***	0.0005
Information development level	0.3681 ***	0.4072 ***	0.0005
Intercept	0.0748	0.0000	0.0000
	$R^2 = 0.4900$ ***	Adjusted $R^2 = 0.4870$ ***	0.0000

Note: *** indicate significance at the levels of 0.001.

The regression coefficient of the relationship matrix between the EDL and the urban informatization development level is significantly positive at the 1% level, indicating that the high EDL promotes the improvement of the linkage intensity of tourism eco-efficiency. The stronger the economy is, then there will be better circulation of the tourism production resources and better linkages between the tourism eco-efficiencies among the cities. This conclusion is consistent with the study of Liu et al. [22,52–54]. Meanwhile, the higher the IDL is, then the more convenient and efficient the circulation of the tourism production factors and the transfer of materials and information will be, which improve tourism eco-efficiency. This conclusion is consistent with the findings of Wang et al. [18,55].

The DBC is significantly negative at the 1% level, indicating that a more distant geographical location is essential to strengthen the correlation between the tourism development efficiencies among the cities, and the more distant the geographical distance between the efficient and inefficient cities is, then the less conducive it is for the transfer and circulation of production factors and information, thus hindering the improvement of the correlation intensity of tourism eco-efficiency. This finding is in line with that of Cheng et al. [56].

The difference matrix of the TIL is not significant, indicating that tourism capital insignificantly hinders the inter-city tourism production cooperation. The capital is usually concentrated in the economically developed cities, which increases the gap between the cities with high and low tourism eco-efficiencies; however, whether it hinders the development of the spatial correlation network of tourism eco-efficiency is not obvious.

4. Conclusions

4.1. Findings

This study established an index system for the measurement of tourism eco-efficiency. The values of tourism eco-efficiency of 26 cities in the Yangtze River Delta from 2009 to 2019 were measured using the undesirable output super-SBM model. In addition, the spatial correlation matrix of tourism eco-efficiency was constructed using the modified gravity model. The spatial correlation of tourism eco-efficiency and its influencing factors were analyzed using the social network analysis.

Firstly, our study differs from previous studies that simply measured the tourism eco-efficiency of a tourism destination and analyzed their spatiotemporal differences [16]. This study argues that the tourism eco-efficiencies of different regions have spatial correlations and are not independent of each other. Based on the analysis of the spatial differences of the tourism eco-efficiencies of the cities in the Yangtze River Delta, this study combined the social network and the geographic information system analyses to construct a spatial correlation network of tourism eco-efficiency, which facilitates the extension of the original "point measurement" of tourism eco-efficiency to the level of "surface evaluation", and also allows for a comprehensive and in-depth exploration of its internal correlations to be made, thus enabling more insightful conclusions to be drawn. Strategically, this combined social network analysis and geographic information system approach can facilitate research on the formation, evaluation, and evolution of the spatially linked networks of tourism eco-efficiency.

Secondly, the driving factors for the formation of the spatial association network of tourism eco-efficiency are analyzed to expand the scope of research. At present, scholars mainly focus on the influencing factors of the spatiotemporal evolution of tourism eco-efficiency [8,51], and much less research has been conducted on the driving factors of the formation of the spatial association network of tourism eco-efficiency. Therefore, the QAP analysis was applied to measure the influence of various driving factors on the nature, direction, and intensity of the spatial linkages of tourism eco-efficiency. The results show that the EDL, the DBC, and the IDL are key factors that have significant effects on the spatial correlation network of tourism eco-efficiency in 26 cities in the Yangtze River Delta. In addition, the nature, direction, and degree of influence of various driving factors vary.

The empirical results verify that the tourism eco-efficiencies of 26 cities are spatially correlated with spatial differentiation patterns and dynamic development trends. On the one hand, tourism eco-efficiency shows an overall growth trend, indicating that with the formulation and implementation of tourism energy conservation and reduction projects in various cities, the construction of the ecological civilization has been continuously promoted. Therefore, the impact of the tourism economic activities on the ecological environment is reduced thereby promoting the maximization of social and economic benefits. On the other hand, the spatial distribution of tourism eco-efficiency in the Yangtze River Delta is not uniform. The tourism eco-efficiencies of most of the cities are at a medium-to-high level, and some cities show a fluctuating change trend. Ten cities show an increasing trend, and three cities show a decreasing trend.

This study also analyzed the degrees of correlation, the network levels, and the network efficiency values of the spatial correlation networks of tourism eco-efficiency in 2009 and 2019 to effectively judge their scale and evolution in terms of achieving tourism eco-efficiency [38,39]. By comparing the correlation degrees of the spatial correlation network of tourism eco-efficiency in 2009 and 2019, this study finds that all of the cities are interrelated, and there is no "island" phenomenon. The structure of the spatial correlation network of tourism eco-efficiency shows good connectivity, accessibility, and robustness. The network rank is in the lower middle level, and it shows a decreasing trend, indicating that the differences between the cities are shrinking and more core nodes are emerging. Moreover, the network efficiency is at a high level, indicating that there are more correlations and only some redundant relationships in this network.

This study further analyzed the structure of the nodes in the spatial correlation network of tourism eco-efficiency in 2009 and 2019. The degrees of centrality index of the nodes in the tourism eco-efficiency association network were measured to effectively judge their roles, spatial differences, and evolution [38,39]. Shanghai, Suzhou, Nanjing, and Hangzhou had above average degrees of centrality, indicating that these cities have more connections, and they are a priority in the spatial correlation network of tourism eco-efficiency. The point-out degrees of 26 cities were >0, indicating that the tourism eco-efficiency of each city has some spatial radiation. Shanghai, Suzhou, Nanjing, and Hangzhou had higher than average point-out degrees. Yancheng, Taizhou (Zhejiang), Ma'anshan, Anqing, and Chizhou had lower point-out degrees. In terms of the point-in degree, Shanghai had the highest number of receiving relations, up to twenty-four, while Yancheng, Taizhou (Jiangsu) and Anqing had the lowest number of receiving relations of only one. In addition, the tourism eco-efficiency of each city in the spatial association network can produce connections with other cities relatively quickly. Shanghai, Nanjing, Suzhou, and Hangzhou had higher than average centrality values, indicating that they play the role of "core actors" in the spatial correlation network of tourism eco-efficiency, leading to the development of the whole network. The tourism eco-efficiencies of 22 cities, such as Changzhou, Ningbo, and Wuhu, were lower than the average level, indicating that their eco-efficiency of tourism is relatively low, leading to the restrictions of other cities and passive positions in the network. Shanghai, Suzhou, and Nanjing play a significant role as "bridges" and "intermediaries", indicating that they play a key role in the spatial association network of tourism eco-efficiency by connecting well with other cities in the transfer of tourism production factors, and they have a strong control in the network.

The spatial correlation of tourism eco-efficiency of 26 cities in 2019 was further analyzed using the block model. Block I is the "core actor" of the spatial correlation network of tourism eco-efficiency with the maximum spillover relationships, and it presents a "two-point" distribution in space. Block III has the second highest number of spillover relationships, and it is centered around the spatially central actor, and it mostly spills over to block I. Blocks II and IV have the same number of spillover relationships and are located in the outermost layer of the entire network. The mutual spillover relationships among blocks II, III, and IV are fewer, and therefore they are "marginal actors" in the spatial correlation network of tourism eco-efficiency.

The tourism eco-efficiency levels of Shanghai, Hangzhou, and Suzhou are relatively high because of their developed tourism economy and geographical advantages. It is easy for these cities to attract social, economic, and environmental resources from other cities. However, the cities in the other three blocks have a relatively backward economic foundation and a poor geographical location, and their tourism eco-efficiency development level is also relatively low with a high dependence on block I through the spillover effect.

All of the relationships in the spatial correlation network of tourism eco-efficiency originate from block I. In other words, Shanghai, Suzhou, and Hangzhou play driving roles in improving the tourism eco-efficiency of the other cities significantly, thereby narrowing the gap in the Yangtze River Delta region and fully alleviating the Matthew effect.

The formation and development of the spatial correlation network of tourism eco-efficiency are influenced by many factors. The results of the QAP correlation analysis show that the EDL and the IDL and the DBC and the TIL are positively and negatively correlated, respectively, with the development of the spatial correlation network of tourism eco-efficiency. The QAP regression analysis shows that the EDL, the DBC, and the IDL play significant roles in the spatial correlation network of tourism eco-efficiency. Therefore, the improvement of tourism eco-efficiency can be achieved by improving the EDL and the IDL. Meanwhile, the closer the cities are to the high eco-efficiency cities, the more beneficial it is to improve their tourism eco-efficiencies. The TIS, the TIL, and the TRE had no significant relationship with the spatial correlation network of tourism eco-efficiency.

The methods and findings of this research can be useful in enhancing the tourism eco-efficiency in the Yangtze River Delta region of China, and they can be applied to multiple destinations. Further empirical studies by other scholars are required to verify the outcomes of this research.

4.2. Implications

Based on the established tourism eco-efficiency measurement index system, this study used the undesirable output Super-SBM model to measure the tourism eco-efficiency values of 26 cities in the Yangtze River Delta in 2009 and 2019. Then, the gravity model was used to calculate the spatial correlation of tourism eco-efficiency of 26 cities in the Yangtze River Delta, and the relationship matrix was built. Finally, the social network analysis was used to analyze the spatial correlation of tourism eco-efficiency and its influencing factors. This study is a bold attempt, which not only enriches the research content of tourism eco-efficiency, but it also promotes the sustainable development of regional tourism.

4.2.1. Theoretical Implications

Firstly, this study is in line with China’s development goal of achieving an ecological civilization construction, as well as its requirements for high-quality economic development. It is of great significance to enrich the theory of sustainable development and expand the application scope of the sustainable development theory.

Secondly, this study is a bold application of the theory of tourism eco-efficiency. By exploring the tourism eco-efficiency of different cities in the Yangtze River Delta, this study further compares the spatial and temporal differences, the spatial correlation, and the influencing factors. This is the logical starting point for exploring the green and sustainable development of the Yangtze River Delta urban agglomeration. This study is different from previous studies that simply measure the tourism eco-efficiency of a certain tourist destination and analyze its internal spatio-temporal differences. It believes that the tourism eco-efficiency of different regions is not independent of each other, but they have a certain spatial correlation. The overall network structure characteristics of the spatial correlation of tourism eco-efficiency were analyzed from the perspective of their “relationship”.

Thirdly, on the basis of analyzing the spatial differences of tourism eco-efficiency in different cities in the Yangtze River Delta, this study combined the analysis of the SNA and GIS data to build the spatial correlation network of tourism eco-efficiency in the Yangtze River Delta urban agglomeration. This is not only conducive to further promoting the original “point measurement” of tourism eco-efficiency to a “surface evaluation”, but also to comprehensively and deeply explore its internal correlation, so as to draw more insightful conclusions. Strategically, the combination of SNA and GIS can promote the research on the formation, evaluation, and evolution of the spatial correlation network of tourism eco-efficiency.

4.2.2. Management Implications

This study found that the overall level of tourism eco-efficiency in the Yangtze River Delta region is constantly improving, and the tourism eco-efficiencies of most of the cities in the region are also improving. Through the method of the social network analysis, the network characteristics between the cities in the region were further analyzed. This can not only help the government to better coordinate the relationship between the regional economic development and the ecological environment and formulate policies according to the local conditions, but also provide new ideas for the urban development of ecological tourism.

Based on the block model analysis, one core block and three marginal blocks were distinguished in this study. It is helpful for the local government to take into account the characteristics of the different sectors and adopt corresponding management strategies to narrow the gap of eco-efficiency of urban tourism in the region to alleviate the Matthew effect.

In addition, this study also explores the influencing factors of the spatial correlation network of tourism eco-efficiency, which can provide a reference for the government and tourism enterprises to formulate the formation and optimization strategies of the spatial correlation network of tourism eco-efficiency.

4.3. Limitations

This study has some limitations. Firstly, the input–output mismatch problem is prone to occur from the perspective of the multi-factor evaluation [8]. Secondly, this study was unable to obtain the energy input and consumption data for the tourism-related aspects such as aviation, catering, shopping, and entertainment. In addition, air pollution should include also No_x and particulate matter concentration data (e.g., PM5, PM2.5, PM1.0) [57,58]. However, due to the limited number of data, the concentration of nitrogen oxides and particulate matter in the study area was very small, so this aspect is not reflected in the established index system. Thirdly, tourism eco-efficiency evaluation should theoretically cover three dimensions: economy, ecology, and society, including the satisfaction of the local residents and tourists as indicators. Therefore, the evaluation system for tourism eco-efficiency should be further improved, theoretically, to provide reference values. These improvements are necessary to provide a strong support for the design of appropriate policies and appropriate decision making.

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Article

Coastal Wetlands Play an Important Role in the Ecological Security Pattern of the Coastal Zone

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Abstract: The construction of an ecological security pattern can effectively overcome the contradiction between regional human exploitation and ecological protection in the coastal zone. Taking the Xiangshan Bay (XSB) basin as an example, this study identified ecological source areas from three aspects, namely ecosystem services' importance, ecological sensitivity, and landscape connectivity, and then constructed ecological resistance surfaces, identified ecological corridors, and constructed an ecological security pattern. The results show that the natural reserves in the XSB basin were all located in the identified primary ecological source areas, thus indicating the feasibility and reliability of the "importance–connectivity–sensitivity" ecological source identification mechanism in this study. The ecological corridor in the coastal wetland area accounts for about 40% of the total corridor length, which is the link connecting other ecological sources, revealing the important role of coastal wetlands in the coastal ecosystem. Through the ecological security pattern of the XSB basin and field investigation, we put forward suggestions such as clearing *Spartina alterniflora*, restoring salt marsh wetland vegetation, and strengthening follow-up monitoring for the restoration of coastal wetlands. This study is expected to provide reference and guidance for the improvement of coastal zone ecological protection and restoration.

Keywords: China; coastal wetland; ecological source; ecological corridor; ecological security pattern; Xiangshan Bay basin

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1. Introduction

In recent years, with the acceleration of global urbanization, the high intensity of land development, and the rapidly changing land use have made the contradiction between ecological protection and development of human society increasingly noticeable; especially in coastal areas of biodiversity loss and soil erosion, the scarcity of water resources has become more severe, and in this context, the construction of ecological security patterns have become increasingly important in balancing economic development and environmental protection [1–4].

The ecological security pattern is a spatial allocation scheme that optimizes the regional ecological spatial pattern, which is one of the effective ways to maintain the integrity of landscape pattern and regional ecological security [5,6]. In 1898, Ward and Win proposed the urban planning concept of a "pastoral city," pointing out that a ring of suburbs should surround the city to reduce the area of urban expansion and alleviate the phenomenon of ecological deterioration, which has been used in environmental planning around the world until now [7]. In the late 1960s, McHarg proposed the "suitability" analysis method based on the vertical ecological process. This method emphasizes the vertical process and connection of various elements in the landscape unit, which is the superposition of each environmental element and human element. This method was still used to determine the "ecological source" in the ecological security pattern in the following decades [8,9]. In 1995, Forman proposed the landscape ecology research "patch–corridor–base" model, paying attention to the horizontal ecological processes that were difficult to reflect in McHard's research. Forman's research greatly promoted the study of landscape patterns, and since then, the development of landscape ecology has deepened people's understanding of landscape processes [10]. Yu proposed the concept of ecological security pattern based on Forman's study of landscape patterns [11], and his research on Beijing's ecological security pattern in 2009 laid the foundation for the development of ecological security patterns in the past decade [12]. The technical route of the "source–space connection–optimization strategy" proposed by Yu has been constantly enriched and optimized. Related research has also been carried out rapidly, and fruitful research results have been obtained from the construction of the initial theoretical framework, the improvement of the index system, and the realization of technical methods [6,13].

At present, relevant research mainly focuses on the identification and construction of ecological security pattern and uses the rating of the ecosystem as an evaluation indicator. The ecological security pattern construction method of Yu's team has been widely recognized and adopted, and its methodology framework is as follows. First, determine the existing habitat (source) of species diffusion; second, establish the resistance surface according to the difficulty of species diffusion and identify the ecological corridor according to the resistance surface; finally, identify the ecological security pattern according to the ecological corridor. Existing methods for determining ecological source areas mainly use landscape connectivity [14], ecosystem services [15,16], ecological sensitivity [17], and other indicators, among which the identification of ecological source areas is the most important link in the construction of ecological security pattern. The resistance surface is mainly based on the terrain and topography. Ecological corridors, or biological corridors, refer to the spatial types of ecosystems with linear or ribbon-like layouts in the environment, which can communicate and connect with the relatively isolated and dispersed ecological units in the spatial distribution. They can meet the requirements of species diffusion, migration, and exchange, and are an important part of the construction of the regional ecological security pattern. Ecological corridors can be identified by the minimal cumulative resistance (MCR) model [18], patch gravity model [19], and comprehensive evaluation index system. Among them, the MCR model can best simulate the hindrance effect of the landscape on the biological spatial movement process and better express the interaction relationship between the landscape pattern and ecological process. It is widely used in the construction of the ecological network and ecological security pattern [20,21]. In the past decade, the directions of specific exploration and research on the ecological security pattern have varied. In terms of the research scale, multiscale ecological security pattern construction methods of different sizes have been formed. In addition, in terms of research methods, a variety of ecological security pattern construction methods have gradually emerged, such as supply and demand of ecosystem services [22], ecological protection red line [23], ecological importance and sensitivity [24], and source–sink theory [25]. Generally, the research on ecological security pattern is still in its initial stage, with a wide range of research categories and various types, but the research on the mechanism is relatively weak. It is necessary to form a widely recognized unified evaluation system integrated with ecology and social economics [26]. The construction of the regional ecological security pattern mode has continued to improve the index and method, and the validity of the index system is one of the core issues of regional ecological security source recognition. Because there is a lack of understanding of the connotation of ecological security and regional ecological security problems of the specific differences, there are differences in different research scheme selection indicators. Moreover, various indicators have advantages and disadvantages; among them, habitat importance indicators are widely used, mainly focusing on specific ecosystem services such as habitat quality, biodiversity conservation, water conservation, and carbon sequestration and oxygen release. However, when identifying the source areas, the traditional methods only focus on the importance of ecological functions or the risk of functional degradation and only consider the services of the ecosystem to human beings in connotation, but they ignore the response of the ecosystem functions and processes to human activities and changes in the natural environment and the spatial organization structure of the ecosystem itself, resulting in a slightly weak basis for the selection of the source areas [17].

Coastal zones make up just 4% of the earth's total land area and 11% of the world's oceans, yet they contain more than a third of the world's population and account for 90% of the catch from marine fisheries. However, human activities are now threatening many of the world's remaining marine ecosystems and the benefits they provide. Due to coastal development, population growth, pollution, and other human activities, 50% of salt marshes, 35% of mangroves, 30% of coral reefs, and 29% of seagrasses have already been lost or degraded worldwide over several decades [27]. As a typical coastal zone area, the XSB basin has a concentrated population and developed economy. The increase of population and economic development have caused problems such as the decline of regional ecosystem services, the occupation of ecological space, and the continuous threat to biodiversity. It is urgent to solve the problem of coordinated development between people and the environment by building an ecological security pattern. In combination with the rich ecological resources in the XSB basin, this study extracted ecological sources through the importance of ecosystem services and the ecological sensitivity and the landscape connectivity, identified ecological corridors through the minimum resistance model, and comprehensively constructed ecological security pattern, so as to improve the construction method of traditional ecological security pattern, with a view to providing a case reference for the research on the construction of regional ecological security pattern. It also provides reference and guidance for coastal zone ecological protection and improvement of ecosystem services.

2. Research Area and Research Methods

2.1. Overview of the Study Area

This study selected Xiangshan Bay (XSB) as the research area. The XSB is located on the southeast coast of China, between 121°25′ E–122°00′ E and 29°23′ N–29°49′ N; elevation ranges from 0 to 831 m. (Figure 1). The XSB basin is located in the northern extension of the Tiantai Mountain range, and also in the Cathaysian fold belt of the South China fold system. The area from the west of Shiyan Port to Xidian is nearly east–west, and the area from the northeast of Shiyan Port to Fodu Waterway belongs to the northeast syncline. The attitude of the syncline lithology is roughly symmetrical, and the late Jurassic volcanic rocks on the north and south sides are distributed symmetrically, which reflects that the volcanic activity is controlled by the NE trending fault structure of the basement. Since the Cenozoic era, the differential lifting activities between the fault blocks in the XSB basin have been significant. The geomorphic types are mainly broken hills and low-lying plains in front of mountains. Quaternary sediments are exposed in the intermountain plains and coastal areas.

It is a semi-enclosed bay composed of three major parts: the Xiangshan narrow bay, Niubi mountain waterway, and Fodu Waterway. The coastline of the XSB has a total length of about 400 km and a unique geographical location. It is an important station on the migration line of waterfowl from East Asia to Australia, an important forest ecological source and water conservation area, and a national aquatic germplasm resource protection zone for economic fish. As a typical coastal zone, the XSB basin has a coastal wetland covering 133.21 km^2, which accounts for 8.5% of the area of the XSB basin and provides material production, environmental regulation, and rich biodiversity for the surrounding residents. Thus, the coastal zone is an extremely important ecosystem in the XSB basin.

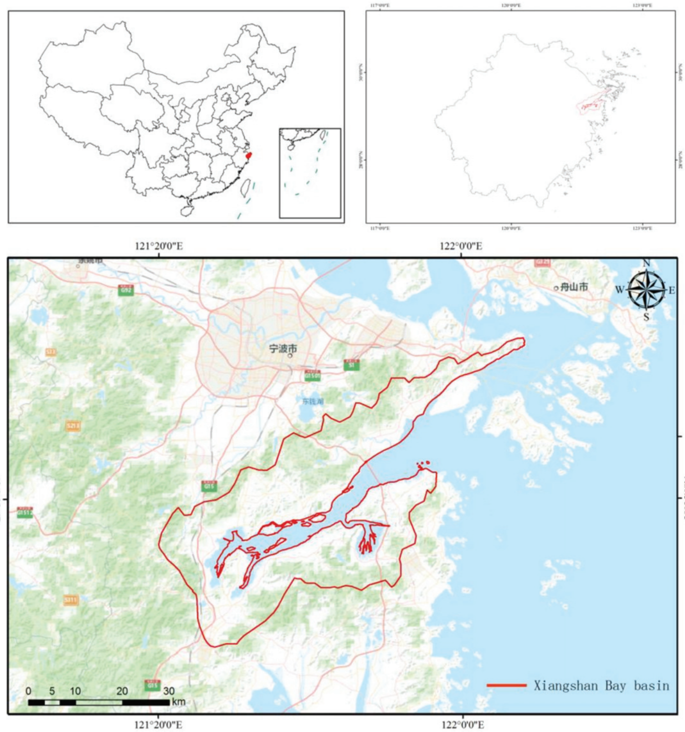


Figure 1. Study area.

2.2. Data Sources and Software Usage

The data used in this study mainly include land-use data, meteorological data, the digital elevation model (DEM), soil data, and the distribution of forest scenic spots. The land-use data used in this paper were obtained from the Data Center for Resources and Environmental Sciences, and Chinese Academy of Sciences, and they were divided into seven categories (Figure 2). The meteorological data were obtained from the China greenhouse data system, and the basic meteorological data of the XSB basin were obtained by using the ArcGIS 10.2 software spatial interpolation tool for meteorological data. The forest scenic vector data were derived from Google Earth software. The basic spatial unit of this study is a 30 m resolution grid. The software and modules used in each single-factor evaluation are shown in Table A1 of Appendix A.

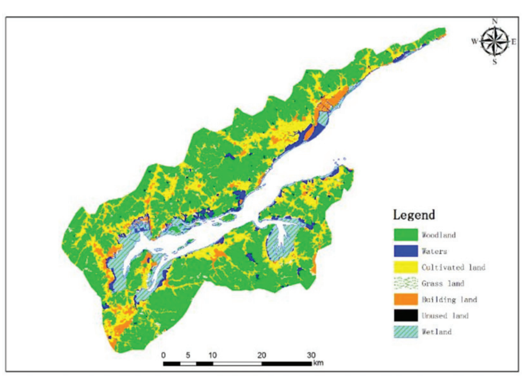


Figure 2. Land-use types in the study area.

2.3. Research Methods

2.3.1. Identification of the Ecological Source

The ecological source refers to the source point of interregional species diffusion, as well as ecological function flow and transmission, which is an area that must be protected to maintain regional ecological security and sustainable development [28]. In this study, the ecological conservation importance classification of the XSB basin was obtained by stacking the grid layer of ecological service importance, ecological sensitivity, and landscape connectivity and then identifying the ecological source.

(1) Importance of ecological services:

According to the environmental characteristics of the XSB basin, the comprehensive evaluation of ecosystem services was carried out from the three aspects of water conservation, carbon fixation and oxygen release (NPP), and habitat quality, and the evaluation results were modified by forest scenic area.

Among them, water conservation and habitat quality were measured by the water yield and habitat quality modules of the integrated valuation of ecosystem services and trade-offs (InVEST) model [29]. The carbon fixation and oxygen release were measured by the NPP estimation plug-in of ENVI 5.3 software. The importance of the abovementioned ecosystem service functions was classified into 5 levels and assigned values from 1 to 5. The higher the value, the higher the ecosystem service level. For the forest scenic area correction, we downloaded the vector data of the XSB basin forest scenic area, assigned 5 to the forest scenic area, and assigned 1 to other areas. The evaluation results of the importance of ecological services were obtained by superposing the equal weights of the classified ecosystem services. The importance classification was carried out by using the natural breakpoint method, and the results are generally important, relatively important, moderately important, highly important, and extremely important, marked as 1, 2, 3, 4, and 5, respectively [30].

(a) Evaluation of water conservation function:

The meteorological data of 87 meteorological stations in five provinces on the east coast of China in 2017 were collected by the China Greenhouse Data System, including precipitation, real-time atmospheric pressure, air humidity, wind speed, and temperature. The basic meteorological data of the XSB basin were obtained by using the Arcgis10.2 software spatial interpolation tool. Evapotranspiration data of the XSB basin were retrieved by the surface energy balance principle (SEBS) model of ILWIS open 3.8.1.0 software. The data on soil depth, soil texture, and soil organic matter content were obtained from the national soil database, and the available water content of plants (PAWC) was calculated. By referring to the reference value of the crop coefficient of FAO and the research results of other scholars [31], we obtained the biophysical number table of each land-use type (Table 1). Finally, the Water Yield module of the InVEST model was used to import all data to calculate the water conservation data of the XSB basin [32].

Table 1. Biophysical parameters of each land-use type input into InVEST water production module.

Land Use	Lucode	Kc	Root Depth (mm)	LULC Veg
Cultivated land	1	0.65	2100	1
Woodland	2	1	7000	1
Grassland	3	0.65	2600	1
Water	4	1	10	0
Building land	5	0.001	10	0
Unused land	6	0.001	10	0

(b) Evaluation of carbon fixation and oxygen release (NPP):

Based on the meteorological interpolation data obtained in the process of water conservation calculation, the radiation data and vegetation type data in 2017 were collected, and the NPP grid data of the XSB basin were calculated through the NPP inputs of ENVI 5.3 software (CASA model). The static parameters of the data required for the model are automatically configured by the software. The vegetation-type map, NDVI data, and meteorological data were collected from the Internet.

(c) Habitat quality assessment:

The habitat quality was obtained by using the habitat quality module of the InVEST model, in which cultivated land, rural residential areas, urban residential areas, roads, and industrial land were regarded as threat sources. By setting the relative influence of each threat source (the weight of a stress factor indicates the relative destructive power of a stress factor to all habitats, from 0 to 1), we obtained the distance between the habitat grid and the threat source, and the sensitivity level of the habitat to the threat source (Table 2). For the weight of the stress factor and the distance between the context grid and the threat source, we referred to other relevant studies [33–35]. The sensitivity of the threat source (Table 3) was set according to the basic principles of biodiversity protection and the basic theories of ecology and landscape science. For example, the sensitivity of natural lands, such as forests and grasslands, is high, and the sensitivity of roads and industrial land is low. The value is between 0 and 1. The closer the value is to 0, the smaller the sensitivity, and vice versa. Habitat suitability is a habitat score given to each land type, with a range of 0–1. The higher the score, the better the habitat suitability of the land type. The habitat suitability of various habitats and the related parameters of their sensitivity to threat factors were mainly based on the research results of other scholars [36]. The habitat quality map was generated by the distance attenuation method and exponential attenuation method.

Table 2. Main threat sources affecting habitat quality.

Threat Source	Maximum Impact Distance (km)	Weight	Recession Way
Cultivated land	0.5	0.5	Linear
Rural residential land	5	0.6	Exponential
Urban residential land	10	1	Exponential
Transport land	5	0.6	Exponential
Industrial land	8	0.7	Exponential

Table 3. Threat source sensitivity assignment.

Land Use	Suitability of Habitat	Cultivated Land	Rural Residential Land	Urban Residential Land	Transport Land	Industrial Land
Cultivated land	0.5	0.3	0.7	0.5	0.3	0.6
Woodland	1	0.3	0.6	0.7	0.5	0.7
Grassland	0.7	0.55	0.65	0.7	0.6	0.6
Water	0.8	0.5	0.6	0.8	0.8	0.8
Construction land	0	0	0	0	0	0
Other land	0.1	0.1	0.2	0.2	0.2	0.2

(d) Forest scenic area correction:

Vector data of forest scenic spots can be downloaded through Google Earth. The data of forest scenic area were used as correction factors after the superposition of water conservation, NPP, and habitat quality.

(2) Ecological sensitivity:

Ecological sensitivity assessment is a comprehensive assessment of the possibility and degree of ecological imbalance and environmental problems when human activities interfere in a certain area. It reflects the possible ecological consequences of human activities [37]. The higher the regional ecological sensitivity, the worse the stability of the ecosystem, and the more easily ecological and environmental problems occur. After comprehensively considering the availability of data, resolution accuracy, data reliability, and academic recognition, we finally selected the normalized difference vegetation index (NDVI), elevation, slope, and land-use type to build an index system. The corresponding range of high, medium, and low sensitivity was divided for each impact factor. According to the index weight determined by Wang's research [38] combined with the actual situation of the research area, the sensitivity evaluation results of the abovementioned five categories of factors were weighted (Table 4), and the ecological sensitivity evaluation map was formed.

Table 4. Ecological sensitivity index system.

Evaluation Factor	Sensitivity Assignment					Weight
	1	3	5	7	9	
Land use	Building land	Unused land	Cultivated land	Woodland, grassland	Wetland, water	0.32
NDVI	0–0.25	0.25–0.5	0.5–0.65	0.65–0.8	>0.8	0.28
DEM (m)	≤60	60–150	150–250	250–400	>400	0.2
Slope (°)	≤5	5–15	15–25	25–35	>35	0.2

(3) Landscape connectivity:

Landscape connectivity is a measure of the continuity between landscape spatial structural units. High landscape connectivity is conducive to the maintenance of ecological processes and biodiversity. This study analyzed the landscape connectivity through the morphological spatial pattern analysis method (MSPA); classified the landscape by using guidos Toolbox 2.8; took ecological land such as forest land, wetland, grassland, and water as the foreground; and took other non-ecological land as the background. After obtaining the grid map, ArcGIS 10.2 software, the plug-in modules Conefor inputs, and Conefor Sensinode 2.6 were used to calculate the landscape connectivity. The overall index of connectivity (IIC) and the probability of connectivity (PC) were used to evaluate the connectivity of the landscape in the study area [39]. On the basis of the connectivity index calculation, the importance dIIC of each patch, that is, the importance of each landscape patch to the overall connectivity, was calculated to characterize the patch connectivity importance. In the calculation of the patch connectivity index, the threshold of patch distance was set to 500 m, and the connectivity probability was set to 0.5. The calculation formula is as follows:

$$\text{dIIC} = (\text{IIC} - \text{IICremove})/\text{IIC} \times 100\% \quad (1)$$

In the formula, dIIC represents the change of PC after a patch is removed, which is used to measure the importance of the patch to maintain landscape connectivity. IICremove is the overall index value of the remaining patches after removing a single patch, and IIC is the overall connectivity index of the patches. As the radiation effect of fine patches is limited, the 10 patches with the largest area (more than 20 km^2) were selected as the ecological source.

2.3.2. Resistance Surface Analysis

The resistance that species and ecological functions need to overcome in the process of controlling and covering space is called ecological resistance. The larger the ecological resistance value, the more difficult the spatial movement of species, and the more ecological services and ecological functions that are lost in the flow process [40]. When a species makes necessary spatial movement owing to its own habits or environmental changes, it preferentially chooses the same or similar land-use type as its original habitat. Animals and plants are sensitive, and in the process of covering large-scale space, they choose to move in space within the patch. According to the main land-use types in the XSB basin, the relative resistance coefficient values were assigned to seven patch types in different regions, and the ecological resistance surface based on land-use types was obtained.

The setting of the resistance value based on land-use type only covers up the difference in ecological resistance within the same land type. Therefore, elevation and slope were selected as the other two factors, which were superimposed with the resistance surface formed based on the land type to form a comprehensive resistance surface in the study area and more accurately represent the difference in regional ecological resistance. The index system of resistance surface construction is based on the index weight determined by combining the research of Wang (2020) and Wang (2021) with the actual situation of the research area [38,41] (Table 5).

Table 5. Index system of resistance surface construction.

Resistance Factor	Classification	Resistance Value	Weight
Land use	Woodland	1	0.5
	Wetland, grassland	10	
	Water	30	
	Cultivated land	50	
	Other land	70	
	Building land	100	
Slope	≤5	10	0.25
	5–15	30	
	15–25	50	
	25–35	70	
	>35	100	
DEM	≤48	10	0.25
	48–121	20	
	121–205	40	
	205–302	60	
	302–421	80	
	>421	100	

2.4. Construction of Ecological Security Pattern

An ecological corridor refers to the linear or ribbon ecological landscape connecting the ecological source. It connects the ecological source; is the carrier of species spatial movement and ecological function flow; is the key ecological land to ensuring the ecological flow, material flow, and energy flow between regions; and reflects the connectivity and accessibility of the source [42]. The MCR model was selected, and the low resistance channel between the ecological source sites was extracted as the ecological corridor by using the created ecological source sites and ecological resistance surfaces based on the spatial analysis tool of ArcGIS 10.2. Through the identification of ecological sources and the extraction of ecological corridors, the most basic ecological security network in the study area was formed.

3. Results

3.1. Ecological Source

The distribution map of the ecosystem service generation area in the study area is shown in Figure 3. The water yield decreases from the mountain forest land on both sides to the coastal wetland ecosystem near the sea area in the bay, urban living areas, and other areas with low vegetation coverage, which is closely related to the land-use type. The capacity of carbon fixation and oxygen release is reflected by the net primary productivity (NPP) of vegetation and decreases from the mountain forest land outside the bay to the urban residential area and the coastal wetland in the bay. The habitat quality of the XSB basin is relatively high on the whole. The forest ecosystems on both sides are the core of the whole basin. From the forest ecosystem to the surrounding agricultural area and then to the coastal wetland ecosystem, the habitat quality gradually decreases. The area with the lowest habitat quality is the residential area, which has been completely transformed into urban and rural residential areas by humans. The natural scenic spots, such as forest and water ecosystems, are all areas with excellent ecological conditions. The grid layers of the four ecological-service-importance evaluation results were superimposed to obtain the spatial pattern of the ecological service importance of the XSB basin (Figure 4). The extremely important area covers an area of 555.54 km^2, accounting for 35.25% of the total area of the whole region. The highly important areas are mainly distributed in the area of 485.40 km^2, accounting for 30.80% of the total area of the whole region. They are all distributed in the mountains, hills, rivers, lakes, reservoirs, and other areas with high ecological service value.

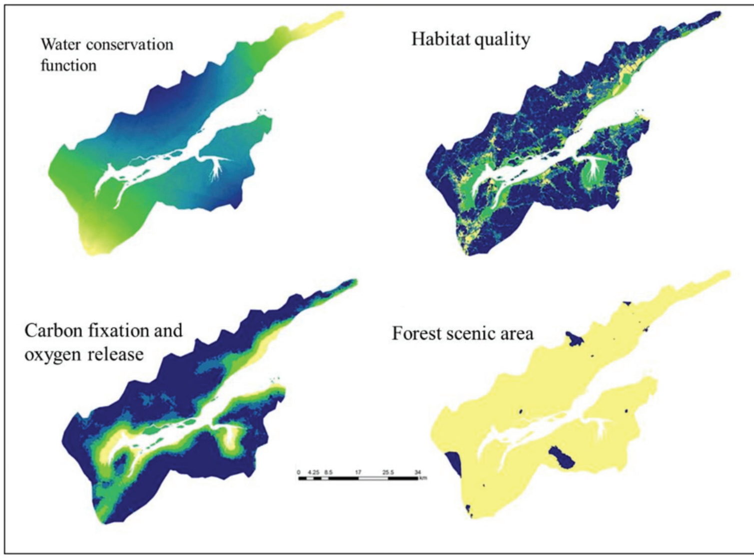


Figure 3. Spatial distribution of ecological service-generating areas.

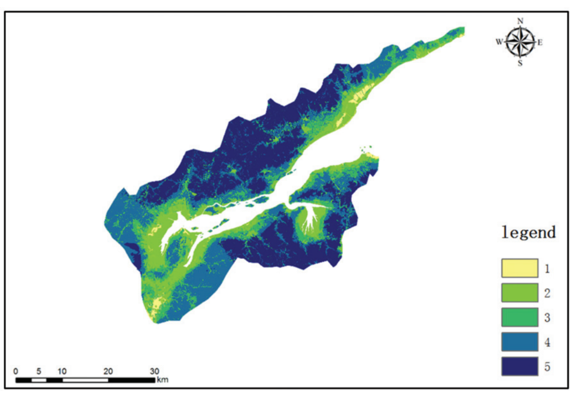


Figure 4. Spatial pattern of the importance of ecological services.

According to the ecological environment sensitivity evaluation method and index system constructed in this study, the ecological sensitivity of the XSB basin was evaluated by single-factor and comprehensive evaluation. The spatial pattern of the ecological sensitivity of each index is shown in Figure 5. The sensitivity of the land-use type gradually decreases from coastal wetlands on both sides of the bay to mountain forest land and then to urban residential areas, which are closely related to the diverse land-use types in the study area. NDVI sensitivity decreases from mountain forest land to coastal wetland in the bay, which is related to vegetation coverage in different areas. The sensitive areas with high elevation and slope are mainly distributed in mountainous and hilly areas. The grid layers of the four ecological sensitivity evaluation results were superimposed to obtain the spatial pattern map of the ecological sensitivity of the XSB basin (Figure 6). The extremely sensitive area is 395.17 km^2, accounting for 25.01% of the area of the study area, and the highly sensitive area is 388.03 km^2, accounting for 24.56% of the area of the study area. The two areas are distributed in mountains, hills, rivers, lakes, and reservoirs. The land-use types are mostly forest land and water, the vegetation coverage is high, and the water resources are rich and fragile, making the areas vulnerable to damage caused by natural disasters or manmade development. The slightly sensitive area is 318.62 km^2, accounting for 20.17% of the study area. It is mainly distributed in the coastal wetland area, which is more stable than the forest ecosystem.

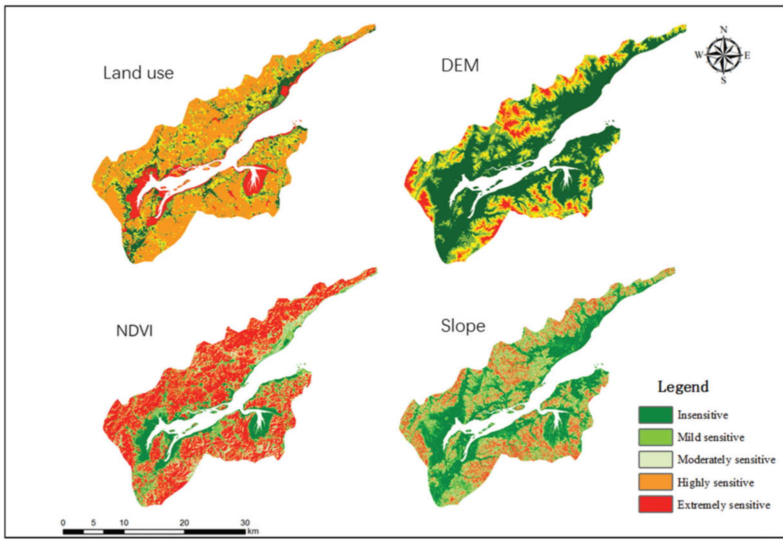


Figure 5. Evaluation results of ecological sensitivity indicators.

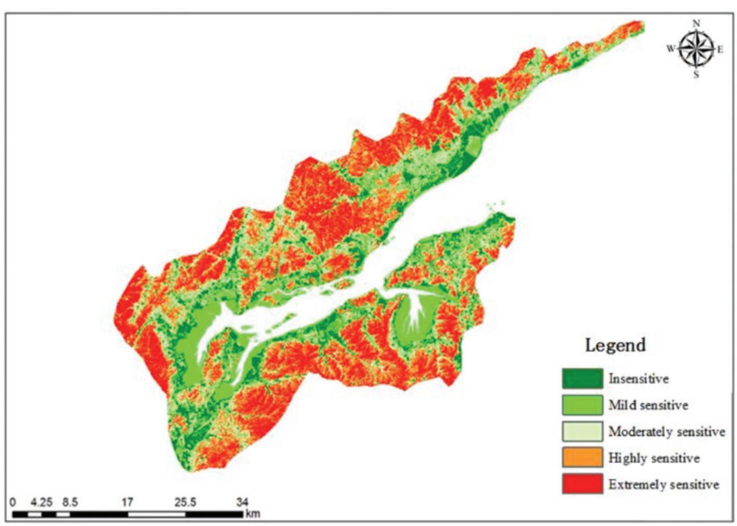


Figure 6. Spatial pattern of ecological sensitivity.

The assessment results of landscape connectivity are shown in Figure 7. The high-value areas of connectivity are mainly distributed in the forest ecosystems on both sides of the

XSB basin. The forest ecosystems on both sides of the XSB basin run through and connect most of the study areas, so the connectivity is high. The low-value areas of connectivity are mainly affected by human activities and their surrounding areas. The transformation of the ecosystem landscape by human activities greatly reduces the connectivity of each landscape patch. According to the arrangement of 30 ecological source patches in the XSB basin in the order of area and landscape connectivity (Figure 8), it can be concluded that the landscape connectivity of each patch in the study area is in direct proportion to the area. With the reduction of the patch area, the landscape connectivity gradually decreases to zero, indicating that although the number of patches removed is large, the area is small and the distribution is discrete, so they have little impact on the overall pattern of landscape connectivity.

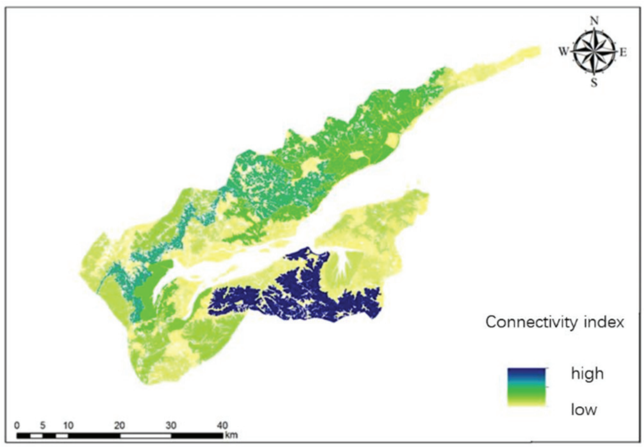


Figure 7. Landscape connectivity of the XSB basin.

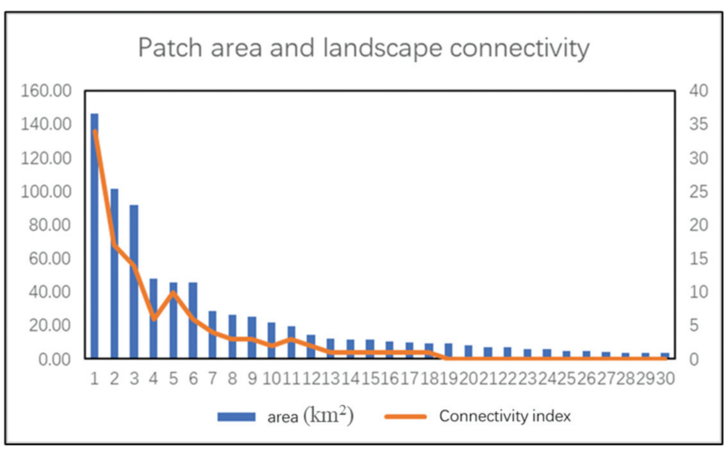
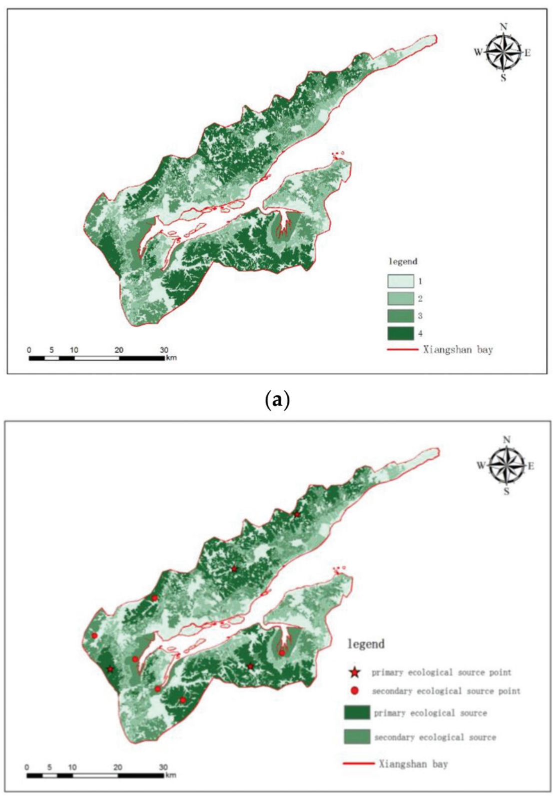


Figure 8. Patch area and landscape connectivity.

The landscape connectivity, ecological service importance evaluation map, and ecological sensitivity evaluation grid map were superposed with equal weight to form a spatial pattern of ecological protection importance (Figure 9a) to identify the ecological source. According to the specific situation of the study area, the importance of ecological protection in the study area is divided into four levels. The higher the level, the more important the ecological protection. The two-level ecological source areas are distinguished to ensure the integrity of the ecological process. The ecological source areas are selected in the Level 4 and Level 3 areas of ecological protection importance. Among them, the Level 4 area of ecological protection importance is the first level's source area, with an area of 444.91 km^2, accounting for 28.16% of the total area. The Level 3 area is the second level's source area, with an area of 367.13 km^2, accounting for 23.24% of the total area. According to the two-level ecological source areas, 10 ecological source points are determined, of which 4 primary ecological source points are in the area of ecological protection importance Level 4, and 6 secondary ecological source points are in the area of ecological protection importance Levels 4 and 3 (Figure 9b). As far as the distribution characteristics of the XSB basin are concerned, the ecological source areas are mainly distributed in the mountainous forest land, the surrounding areas of the water source areas, and the coastal wetland areas. It is worth mentioning that coastal wetlands are mainly distributed in secondary ecological sources, which may be related to the degradation of coastal wetlands.



(**a**)

(**b**)

Figure 9. Spatial pattern of ecological protection importance (**a**) and Spatial distribution of ecological sources (**b**).

3.2. Minimum Accumulated Resistance Surface

Based on the spatial difference of ecological resistance formed by XSB, as shown in Figure 10, the ecological resistance values of most forest lands and other ecological areas in the study area are small. Owing to the correction of elevation and slope, the resistance values of mountain forest lands in different areas are different, which is more in line with the actual situation. The area with the smallest resistance value is the forest land in the low-lying area and the coastal wetland area, so the area is transformed into the area of human activities. The resistance value gradually increases and reaches the maximum value in the residential area.

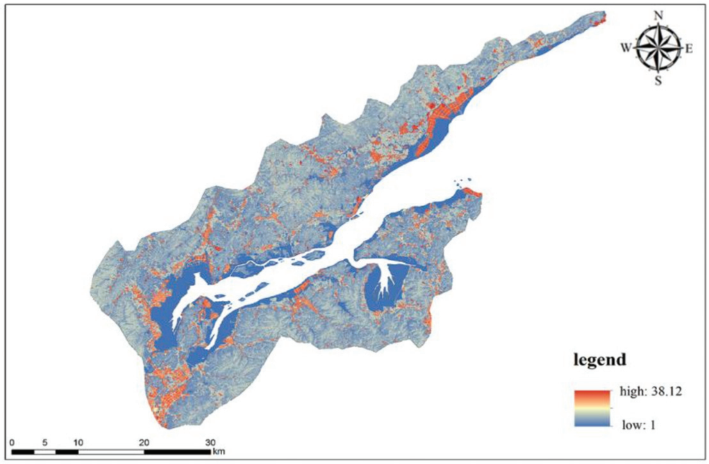


Figure 10. Spatial difference in ecological resistance.

3.3. Key Ecological Corridors and Ecological Security Pattern

This study took the XSB basin as the research area, extracted the ecological source through two methods, comprehensively selected the best ecological source through field investigation and data reference, identified the ecological corridor through the minimum resistance model, and finally constructed the ecological security pattern of the XSB (Figure 11). The results show that the primary ecological source area of the XSB basin is 444.91 km^2, and the secondary ecological source area is 367.13 km^2, accounting for 28.16% and 23.24% of the total study area, respectively. The primary ecological source area is mainly distributed in the mountain forest land and water source area of the XSB basin, and the secondary ecological source area is mainly distributed in the mountain forest land and water source area and coastal wetland area. The total length of the ecological corridor is 550.91 km, and there are multiple ecological corridors between the two source areas, which reflects the randomness of species in the spatial movement. On the whole, the ecological corridors between the ecological sources of the XSB basin are connected in two ways. The first way is to connect the sources along the mountain plain and avoid the urban area. The second way connects the sources through the coastal wetland. The ecological corridor in the north of the XSB basin extends from the southwest to the northeast, connecting the YC mountain scenic area, DS river water system, BL Forest Park, and DQ Lake Scenic Area in turn, as well as four secondary sources of forest water. The ecological corridor in the south of the XSB basin is centered on the primary source of the LLT Forest Park, connecting a secondary source of forest water to the southwest and a secondary source of coastal wetland to the northeast. The two ecological corridors in the north and south are connected by an ecological corridor from the northwest to the southeast which runs through the two secondary sources of coastal wetlands. Through the spatial layout optimization of ecological elements, the ecological spatial optimization layout plan of the XSB basin is constructed and is mainly composed of two-level ecological source points, three ecological belts, and four ecological conservation areas (Figure 12).

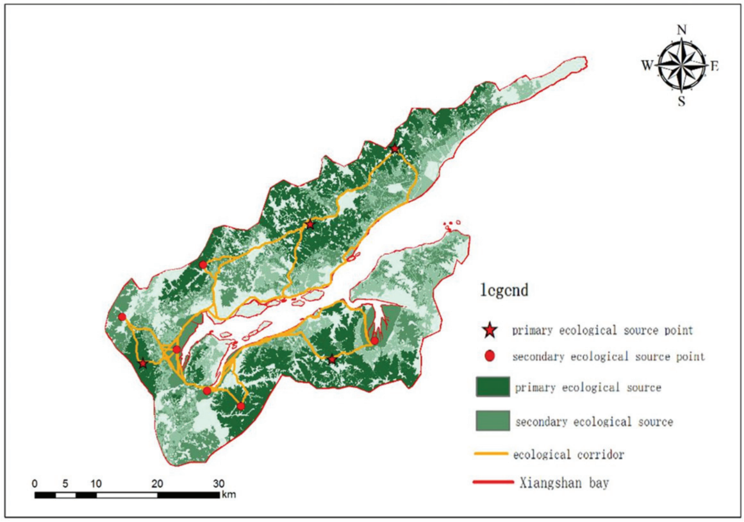


Figure 11. Ecological security pattern of the XSB basin.

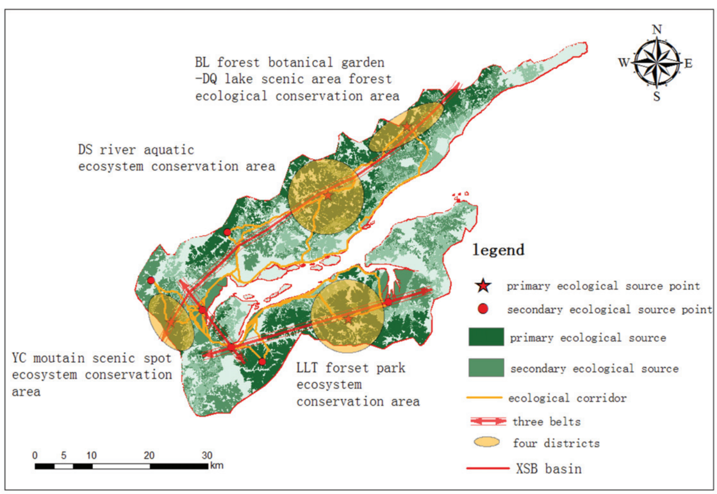


Figure 12. Ecological space optimization layout scheme of the XSB basin.

4. Discussion

4.1. Analysis of Identification Mechanism of Ecological Source

At present, there are two methods for identifying the ecological source: the direct identification method and the building comprehensive evaluation index system method. The direct identification method usually selects natural scenic spots as the ecological source, but there are strong subjective factors. The method for building a comprehensive evaluation index system is usually based on factors including ecological suitability, ecological risk, ecological importance, and ecological connectivity, of which the ecological importance assessment based on ecosystem services is the most important and commonly used [43,44]. However, these methods focus on the functional attributes of the ecosystem [45], ignoring the impact of landscape connectivity on ecological processes and ecological functions at different scales [46,47]. Therefore, this study added landscape connectivity to identify the ecological source. With landscape connectivity, the classification of the landscape in the study area was mainly based on the land type and the area of the connected patches. This method could effectively identify the ecological source in the study area. According to the research results of this paper, the removed fine patches had little impact on the connectivity of the whole habitat, and, thus, they had little impact on the distribution of the ecological source. This agrees with the research results of Wu and others. Through the combination of landscape connectivity and other indicators to identify the ecological source in Shenzhen, the research results show that, although the number of patches removed was large, the area was small and the distribution was relatively discrete, so the impact on the overall pattern of the ecological source was small [48]. In specific research, a certain perspective or a combination of multiple perspectives is usually selected to determine the ecological source. In this study, the importance of ecological services, ecological sensitivity, and landscape connectivity were combined to identify the ecological source. In recent years, this approach has been favored by many researchers in the identification of ecological sources [17,49]. According to the identification results of the ecological source of the XSB basin in this study, the ecological source is mainly distributed in the mountain forest land and water source, which agrees with the results of many scholars. Wu et al. identified the ecological source of Shenzhen through the combination of landscape connectivity, biodiversity, and habitat quality and constructed an ecological security pattern. The results show that the important patches in the ecosystem were basically distributed in the mountains, and the ecological source was mainly composed of forest land [50]. Peng et al. identified the ecological source of Yunnan province based on the importance of ecological services, combined with biodiversity and habitat quality, and constructed the ecological security pattern through the minimum resistance model. The results show that the ecological security pattern of Yunnan province was composed of ecological sources dominated by forest land, and radial ecological corridors were distributed along mountains and forest belts [51]. Moreover, the nature reserves in the XSB basin were located in the primary ecological source identified in this study, and the coastal wetlands, one of the important ecosystems in XSB basin, were located in the secondary source, which, to a large extent, indicates the feasibility and reliability of this identification method.

4.2. The Important Role of Coastal Wetlands in the Ecological Security Pattern of the Coastal Areas

The ecological corridor can achieve the following ecological services: movement and diffusion, lasting maintenance of species diversity, habitat connectivity, and gene exchange. The aim is to maintain a healthy ecosystem. Therefore, the ecological corridor plays a decisive role in the whole ecosystem [52]. The XSB basin has 133.21 km^2 of tidal flats, accounting for 8.5% of the area. It provides people with material production, environmental regulation, and rich biodiversity and is an important ecosystem in the XSB basin. From the identification results of ecological corridors in the XSB basin, the ecological corridors connecting various ecological sources eventually converge in the coastal wetland area, accounting for about 40% of the total corridor length. The coastland wetland area occupies the most important position in biological migration and species exchange among ecological sources and is the link connecting other ecological sources.

The coastal wetlands in the XSB basin play a key role in the ecological security pattern. From the perspective of building the minimum resistance model, the ecological resistance value of the coastal wetland area is the lowest, and the two ecological belts in the north and south are connected by two ecological sources of the coastal wetland, so they occupy a pivotal position in the distribution of ecological corridors. Zhan built an ecological security pattern composed of coastal ecological corridors and landscape ecological corridors in Weihai, Shandong province, China, by combining the importance of ecosystem services and ecological sensitivity with the ecological red line. The coastal ecological corridors cover the whole coastline of Weihai, providing an important guarantee for the biodiversity and biological migration and diffusion of Weihai [53]. Similarly, Wu constructed the wetland ecological network of the Yellow River Delta based on the minimum resistance model. By comparing the ecological resistance values between different land-use types, she found that the natural wetland and water area were the best distribution areas of the ecological corridor, while the human activity transformation area was rarely distributed [54]. All of these results prove that the coastal wetland regional ecological corridor is the most economical path for the spatial movement of biological species.

The coastal wetland in the XSB basin plays an important role in the ecological security pattern, and from the perspective of coastal ecological service functions, the coastal wetland is the ecosystem with the largest biomass and rich biodiversity, which is conducive to biological migration and diffusion in the whole habitat. According to the survey data from 2006 to 2009, 158 species of intertidal organisms have been identified in the XSB, mostly mollusks and crustaceans. The abundant intertidal organisms are secondary consumers in the ecosystem, which shows not only the abundance of phytoplankton as primary producers and floating animals as primary consumers in coastal wetlands but also the existence of other consumers at the top of the food chain [55]. The organisms in the coastal wetland area not only can diffuse to the surrounding area through the coastal wetland but also provide a habitat and food source for other migratory organisms. Comparing 1981 with 1990, the biomass in the intertidal zone of the XSB has decreased significantly, which is because of the rapid increase in the population of coastal cities and towns. The rapid development of the port industry and the vigorous development of marine aquaculture, human factors, and natural factors such as Spartina invasion have caused damage to the coastal wetland ecology to a certain extent. However, there is evidence that the construction of artificial wetlands and the restored coastal wetlands have greatly improved the biodiversity of habitats. According to the statistics of many studies, the biodiversity of wetlands after restoration has increased by 40% [56]. According to the survey, nine wetland restoration projects have been carried out in the wetlands on both sides of an inner bay in the XSB basin. Before and after the restoration, the number of birds increased from 886 of 37 species to 10,206 of 43 species. Zhang investigated the ecological environment of the newly built artificial wetland in a coal mining subsidence area; carried out in situ sampling and positioning research on the plant diversity, benthic invertebrate diversity, and bird diversity of the newborn wetland; and concluded that there were 271 species of newborn wild vascular plants, 138 species of birds, and 68 species of benthic invertebrates, demonstrating a qualitative improvement in biodiversity [57]. A good coastal wetland ecosystem plays a vital role in maintaining the biodiversity and ecological connectivity of the whole ecosystem, and the migration and diffusion of organisms in the coastal wetland area can only rely on the ecological corridor in this area to a large extent. Therefore, strengthening the construction of an ecological corridor in the coastal wet area is of great significance to the improvement of the biodiversity and ecological connectivity of the whole XSB basin. In addition to providing rich aquatic products, coastal wetland vegetation, especially mangroves, plays an important role in preventing coastal erosion. Zahra Karimi studied the root soil of mangroves along the northern coastline of Qeshm Island, Iran. The results show that mangrove roots can improve soil stability and play an important role in preventing coastal erosion [58]. Coastal wetlands also play an important role in purifying water quality, especially in the absorption, transformation, and retention of nutrients such as nitrogen and phosphorus and heavy metals, which can effectively reduce their concentration in water [59]. The two inner ports in XSB basin have more reclamation and aquaculture, and the original vegetation communities have been destroyed, leading to serious coastal zone erosion, while the areas with better vegetation communities have almost no coastal erosion. Land-sourced domestic sewage, agricultural fertilizer, industrial emissions, and other land-sourced pollutants in the XSB basin are usually combined with sediments. They are degraded, stored, and transformed through the absorption of wetland vegetation and the transformation of chemical and biological processes. The slow water flow speed in the wetland is conducive to the sinking of sediments, and also to the storage and transformation of pollutants combined with sediments. Many aquatic plants in coastal wetlands can enrich heavy metals, thus participating in the process of metal detoxification, which can effectively alleviate the outstanding contradiction between economic and social development and environmental protection. The coastal wetland ecosystem has a strong ecological service function, which plays an important role in maintaining the stability of the ecosystem in the XSB basin.

The wetland habitat has important ecological significance for other migratory organisms; various wetlands distributed along the migration route are particularly important energy supply sources for waterfowl migration, providing food and habitat for different populations [60]. There are more than 870 species of waterfowl worldwide that rely on wetlands for survival, most being seasonal migratory birds [61]. A series of available stop point wetlands distributed along the migration route are the basis for ensuring the success of waterfowl migration. They play the role of relay stations and food supply places in the whole migration network, but they are often the bottleneck in the migration process of many waterfowl populations [62]. The change in the wetland habitat, especially the habitat change of important stopover wetlands of international significance, has a strong impact on the number of waterfowl populations during migration [63]. The coastal wetland in the XSB basin is an important station on the East Asia Australia waterfowl migration line. According to a survey, in the autumn of 2020, there were 85 species in 59 genera, 36 families, and 12 orders of birds in a certain inner port of the XSB. In recent decades, with the intensification of climate change and human activities, natural wetlands have been lost on a large scale, and the coastal wetlands located on the migration route from East Asia to Australia have, in particular, undergone tremendous changes [64]. By the end of the 20th century, more than 50% of the wetlands in the world had disappeared, while China had lost about 33% of the wetlands from 1978 to 2008, and the rest had also been degraded to varying degrees under the interference of human activities [65]. The habitat loss or habitat quality decline of many waterfowl located on the migration route has posed a serious threat to the migratory population [66]. If the existing wetland ecosystem is further damaged, the waterfowl population will lose the suitable wetland as a resting place or wintering place during the migration process. As a result, the population will be unable to complete the migration cycle and will eventually be extinct [67]. A good coastal wetland habitat is a relay station for bird migration. For the XSB basin, the coastal wetland provides an ideal place for birds foraging, migration, and species exchange between ecological patches and plays a crucial role in the maintenance of bird biodiversity.

4.3. Coastal Wetland Degradation and Restoration Strategy

Coastal wetland degradation is a common problem faced by all countries in the world and mainly stems from natural disasters and human factors; natural disasters include typhoons, tsunamis, and biological invasions, and human factors include land reclamation, aquaculture, land-based pollution, aquaculture pollution, coastal vegetation felling, or destruction [68,69], which not only lead to the loss of coastal wetland ecosystem diversity but also seriously weaken the coastal wetland ecosystem function. The restoration of degraded coastal wetland ecosystems has therefore become a hot topic in international ecological research. The restoration objects of coastal wetlands have gradually diversified, covering all types of coastal wetland habitats, such as salt marshes, mangroves, coral reefs, and seagrass beds. The restoration system has changed from a small scale, such as a single habitat, community, or species, to a large scale, such as a region or country. A large number of regional or large-scale coastal restoration projects dominated by developed countries such as Europe have emerged [70,71]. Ecological restoration of coastal wetlands in China has mainly focused on individual projects or local areas, and artificial restoration technology of wetland vegetation and coral.

The global coastal wetland area is about 1.42 million square kilometers, and China's coastal wetland area is about 52,450 km^2 [72,73]. The coastal wetland is a transitional zone between the terrestrial ecosystem and the marine ecosystem. It is composed of a continuous coastal area, intertidal zone, and water ecosystem, including the river network, estuary, salt marsh, and beach. As it is affected by the interaction of sea and land, it is a relatively fragile ecologically sensitive area. It is considered one of the most productive and biodiversity-rich ecosystems. It provides protection against storms and coastal erosion and provides important ecosystem functional services such as aquatic products, water purification, and biodiversity maintenance [74]. The XSB basin has 133.21 km^2 of tidal flats, accounting for 8.5% of the basin area. The coastal wetland provides people with material production, environmental regulation, and rich biodiversity and is an extremely important ecosystem in the XSB basin. According to the importance of ecological services and ecological sensitivity, ecological services of coastal wetlands in the study area are relatively important and moderately important, and the ecological sensitivity is slightly sensitive, which is related to the degradation of coastal wetlands. Some scholars regard coastal wetlands as potential ecologically sensitive areas, which shows that coastal wetland ecosystems are vulnerable to damage and degradation. However, as a potential ecologically sensitive area, it needs to be repaired to better serve its ecosystem service function [75]. According to remote-sensing interpretation and field investigation, the main problem of coastal wetlands in the XSB basin is the invasion of *Spartina alterniflora*. In the 10-year period from 2009 to 2019, *Spartina alterniflora* invaded in large quantities, increasing from 1058 hectares in 2009 to 2587 hectares in 2019, resulting in the decline of beach biodiversity and the reduction of bird habitat. In addition, many coastal wetlands in the study area have been reclaimed from the sea for aquaculture, which has led to the degradation of the coastal wetland ecosystem, the change of hydrodynamic conditions in the bay, the discharge of land-based pollution into the sea, and aquaculture pollution. According to the survey results, the coastal wetland restoration in the study area is a salt marsh wetland restoration type. There are many large-scale regional salt marsh ecological restoration projects in the world, such as in Delaware Bay [76], San Francisco Bay [77], and Chesapeake Bay [78] in the United States. Compared with international research, the research on salt marsh wetland ecological restoration in China is still in its infancy, and it mainly focuses on the restoration and reconstruction of the salt marsh wetland ecosystem, wetland pollution bioremediation technology, wetland invasive species (especially *Spartina alterniflora*) removal, and prevention and control technology. In view of the problems existing in the coastal wetlands in the study area, cutting and flooding can be used to treat a large area of *Spartina alterniflora*, and local dominant species such as *Hibiscus hamabo* and *Bolboschoenoplectus mariqueter* can be cultivated. In addition, salt marsh wetland organisms need to be introduced to complete the restoration and reconstruction of the salt marsh wetland ecosystem. According to the survey, after this method of treatment in Chongming Island, Shanghai, the removal rate of *Spartina alterniflora* can reach more than 95%, and the biodiversity can be greatly improved [79]. For aquaculture, the management department should restore the original ecosystem in an orderly manner according to relevant plans. In addition, an ecological restoration monitoring and effect evaluation system was established to evaluate the governance effect and follow-up monitoring of the coastal wetland environment.

According to the results of the ecological security pattern of the XSB basin, the coastal wetland ecosystem occupies a prominent position in the whole habitat and plays a link role in biological migration and species exchange. However, the coastal wetland ecosystem poses a great threat to the ecological security of the whole basin, owing to habitat degradation. Our suggestions are to carry out salt marsh wetland restoration for the coastal wetland ecosystem, strengthen the construction of green infrastructure in the ecological corridor area, establish an ecological buffer for the coastal wetland area in the XSB basin, and connect the ecological land and non-ecological land in the area to improve the ecological connectivity of the coastal wetland ecosystem in the whole basin and improve the environmental quality of nonecological land. This way, the coastal wetland ecosystem can be built into a unique inner harbor ecological connectivity belt in the XSB basin.

4.4. Deficiencies and Prospects

As the case in this study is an attempt of a new method, there are still some shortcomings: For example, in terms of specific operation methods, when assessing the habitat quality, only the range of the XSB basin is considered, and there will be deviation in the assessment of the threat to the patches at the edge of the study area. In subsequent studies, the habitats at a certain distance from the periphery of the study area can be taken into account. The time series of this study is short, but because there are many evaluation indicators, it will be a huge project to evaluate all indicators according to the time series. In addition, the universal applicability and rationality of this method need to be further verified by more field work and case studies in the future.

5. Conclusions

In this study, the ecological source area of the XSB basin was identified by the method of "importance–connectivity–sensitivity", and the ecological corridor was identified by the minimum resistance model to finally build an ecological security pattern.

The results show that the primary ecological source area of the XSB basin is 444.91 km^2, and the secondary ecological source area is 367.13 km^2, accounting for 28.16% and 23.24% of the total study area, respectively. The natural reserves in XSB basin were all located in the identified primary ecological source areas, which indicates the feasibility and reliability of the "importance–connectivity–sensitivity" ecological source identification mechanism in this study. From the identification results of ecological corridors in the XSB basin, the ecological corridors connecting various ecological sources eventually converge in the coastal wetland area, accounting for about 40% of the total corridor length. The coastland wetland area occupies the most important position in biological migration and species exchange among ecological sources and is the link connecting other ecological sources.

However, according to the results of the construction of the ecological security pattern and the field survey, the ecological services and ecological sensitivity of the coastal wetlands in the XSB basin are reduced, and the habitat is degraded. This study proposes some restoration strategies: cutting and flooding can be used to treat a large area of *Spartina alterniflora*, and local dominant species such as *Hibiscus hamabo* and *Bolboschoenoplectus mariqueter* can be cultivated. In addition, salt marsh wetland organisms need to be introduced to complete the restoration and reconstruction of the salt marsh wetland ecosystem.

Author Contributions: Conceptualization, Q.Y.; methodology, Q.Y. and C.H.; software, Q.Y., S.Z., H.G. and Y.Y.; formal analysis, Q.Y., Y.X. and C.H.; data curation, Q.Y., H.G., S.Z., Y.X., Y.Y. and F.L.; writing—original draft preparation, Q.Y.; writing—review and editing, Q.Y. and C.H.; visualization, Q.Y. and H.G.; supervision, C.H. and K.L. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Software and modules used in each evaluation.

Comprehensive Evaluation	Single-Factor Evaluation	Software	Module
Importance of ecological services	Water conservation	InVEST ILWIS open 3.8.1.0	Water Yield SEBS model
	Habitat quality	InVEST	Habitat Quality
	Carbon fixation and oxygen release	ENVI 5.3	NPP Inputs
	Forest Scenic Area	Google Earth	\
Ecological sensitivity	NDVI	ENVI 5.3	\
Landscape connectivity	\	Guidos Toolbox 2.8 ArcGIS 10.2 Conefor Sensinode 2.6	\ Conefor Inputs \

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A Scenario Simulation Study on the Impact of Urban Expansion on Terrestrial Carbon Storage in the Yangtze River Delta, China

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Abstract: Assessing the impacts and drivers of urban expansion on terrestrial carbon storage (TCS) is important for urban ecology and sustainability; however, a unified accounting standard for carbon intensity and research on the drivers and economic value of TCS changes are lacking. Here, urban expansion and TCS in the Yangtze River Delta were simulated based on Patch-generating Land Use Simulation and Integrated Valuation of Ecosystem Services and Trade-offs models; scenario simulation; Literature, Correction, Ratio, Verification carbon intensity measurement; and land use transfer matrix methods. The results showed that (1) from 2000 to 2020, urbanization and TCS loss accelerated, with 61.127% of TCS loss occurring in soil, and land conversion was prominent in riverine and coastal cities, mainly driven by the urban land occupation of cropland around suitable slopes, transportation arteries, and rivers. (2) From 2020 to 2030, urban land expansion and TCS loss varied under different scenarios; economic losses from the loss of the carbon sink value under cropland protection and ecological protection were USD 102.368 and 287.266 million lower, respectively, than under the baseline scenario. Even if urban expansion slows, the loss of TCS under global warming cannot be ignored. Considering the indirect impacts of urbanization, the failure to establish a regional development master plan based on ecosystem services may affect China's carbon targets.

Keywords: urban expansion; terrestrial carbon storage; PLUS model; InVEST model; scenario simulation; YRD

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1. Introduction

Terrestrial carbon storage (TCS) is the carbon stored in plant leaves, woody parts, and soil during continuous exchanges between the atmosphere, soil, and plants. It is widely recognized as an ecosystem service that plays an important role in understanding the interactive response between climate and productivity [1]. Urban expansion is the process of converting land-use attributes from non-urban to urban areas [2,3]. However, the reduction in vegetation cover and increase in impervious surfaces severely limits the provision of regional ecosystem services and ecological resilience, which in turn leads to an increased loss of carbon storage in terrestrial ecosystems [4]. In recent decades, the world has experienced significant urban expansion, with urban land growing from approximately 7.47×10^5 km^2 to 8.0×10^5 km^2 from 2001 to 2018 [5]. China underwent the most significant urban expansion during this period, accounting for 47.5% of the total [5]. Therefore, a timely and effective assessment of the impacts of urban expansion on ecosystem services (e.g., TCS) has become a critical and urgent task to better understand urban ecology and to achieve sustainable urban development.

The main methods currently used to estimate the impact of urban expansion on TCS are field sampling, image interpretation, and model simulations [6–8]. Model simulations are applied to estimate the impact of urban expansion on TCS owing to their advantages of low cost, speed, and predictability [9]. For example, Seto et al. [10] used a grid-based land change model to project global urbanization development in 2030 and discussed its direct impact on the carbon pool. He et al. [11] linked the Land Use Scenario Dynamics-urban model and the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model to simulate and predict the urban expansion process in Beijing from 1990 to 2030, and they assessed the potential impacts on TCS. Wang et al. [12] integrated a scenario simulation method, system dynamics model, and InVEST model to explore future changes in land use and TCS under different climate scenarios in the Bortala Mongol Autonomous Prefecture, Xinjiang, China, in 2050, which precisely guided local regional development planning.

Models such as CA-Markov, CLUE-S, and future land-use simulation (FLUS) have become important tools for predicting future urban-land expansion [13–15]. However, it is difficult to reveal the underlying factors of land-use change and dynamically capture the evolution of each type of land-use patch [16]. In contrast, the Patch-generating Land Use Simulation (PLUS) model uses the Land Expansion Analysis Strategy (LEAS) module to explore the causal factors of various types of land use changes and simulate multiple land use patch-level changes [17]. The InVEST model consists of a series of modules and algorithms, of which the carbon module can directly combine land-use change and TCS dynamics based on land-use maps and carbon density; thus, carbon density is a key indicator for estimating TCS. Li et al. [18] conducted physical and chemical experiments to determine soil organic carbon density by selecting typical sample areas and land types for soil sample collection. Although field sampling methods are the most basic and effective, they are difficult to implement in large-scale areas because they require cumbersome processes. Moreover, the lack of uniform accounting standards for large-scale carbon density estimation causes the carbon density of different land types in the same region to vary significantly [19]. In the global market economy, the economic value of terrestrial ecosystem carbon sink services has been widely recognized, and some scholars have used the social cost of carbon to study the social and economic value of changes in TCS due to urban expansion [20].

As a scientific innovation, industrial, and financial hub, the Yangtze River Delta (YRD) has experienced rapid economic development and urban expansion since the Chinese economic reform and opening-up [21]. From 1980 to 2020, the per capita gross domestic product (GDP) of the YRD increased from CNY 602.526 to 103,962.565, the urbanization rate increased from 16.395% to 70.847%, and the area of urban construction land increased from 25,700 to 47,138 km^2. It was shown that urban construction land in the YRD grew by 156.25% from 1990 to 2015, while all other land types declined to varying degrees, resulting in an estimated loss of 1210.54 Tg of TCS [22]. These TCS estimates were based on the consequences of shifts in all land types under the influence of climate change and human activities. However, changes in TCS due to shifts in and out of urban land use have not been accurately assessed.

This study aimed to clearly reveal the impact of TCS on urban expansion in the YRD and set three objectives to achieve this: (1) assess the urban expansion and TCS changes in the YRD from 2000 to 2020 based on the coupled PLUS and InVEST models using the Literature, Correction, Ratio, Verification (LCRV) carbon intensity measurement method; (2) analyze and predict urban expansion and the impact on TCS in the YRD in 2030 using the scenario simulation method; and (3) explore the drivers of TCS changes from urban expansion and the loss of the economic value of carbon sinks in different scenarios.

2. Materials and Methods

2.1. Research Area

The YRD is located at the "T" junction along the river and coast of China (114°54′–122°12′ E, 27°02′–35°08′ N), with an area of approximately 350,396.447 km^2, accounting for 3.65% of China's total area (Figure 1). The topography shows a trend of high elevation in the southwest and low elevation in the northeast, with elevations ranging from −210 to 1921 m, and mountains, hills, and plains are distributed sequentially. The YRD is located at the intersection of warm temperate and southern and northern subtropical monsoon climates, with an annual average temperature of 13.6–18 °C, an annual precipitation of 704–2000 mm, and the highest density of river networks in China, providing the region with ideal water and heat conditions. The area has complex vegetation composition, high forest cover, and a wide variety of soil types. The region includes Shanghai, Jiangsu (Nanjing, Suzhou, Nantong, etc.), Zhejiang (Hangzhou, Ningbo, Wenzhou, etc.), and Anhui (Hefei, Wuhu, Chuzhou, etc.) provinces. In 2020, the GDP of the YRD was CNY 24,471.353 billion, and the resident population was 235.386 million.

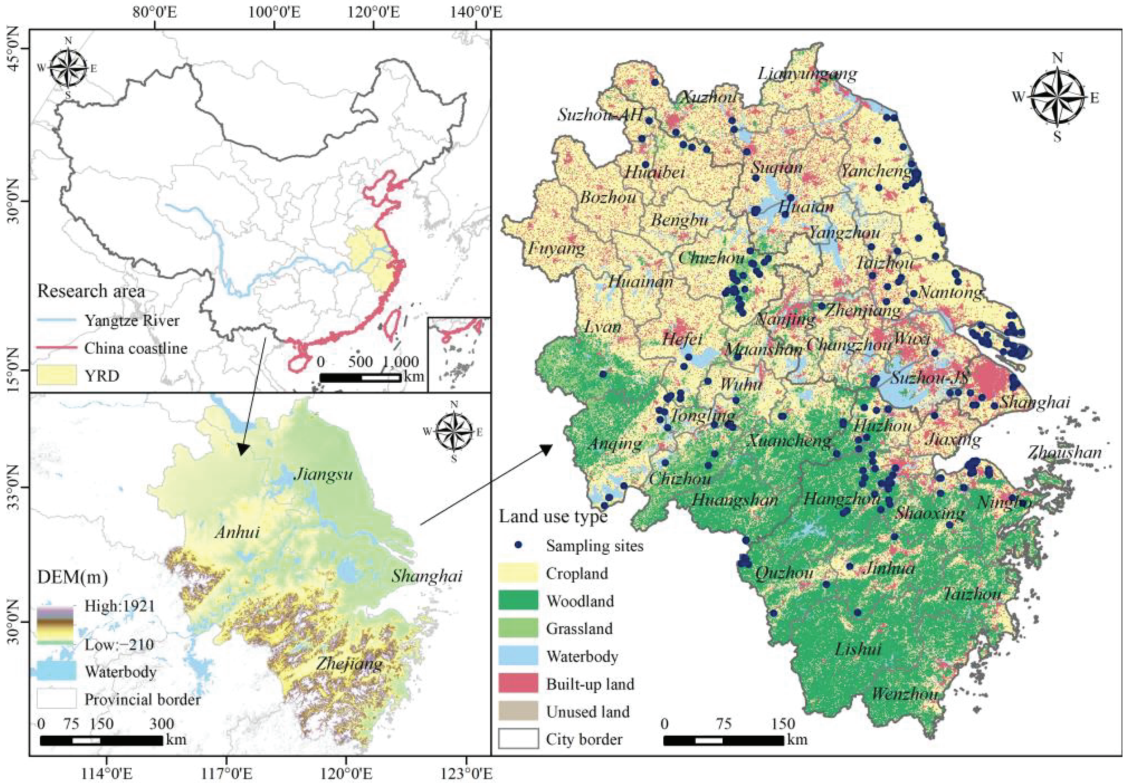

Figure 1. Location, DEM, and land use map of YRD.

2.2. Data Sources

The land use data of the YRD were reclassified into six categories: cropland, woodland, grassland, waterbody, built-up land, and unused land by referring to the land resource classification [23]. Natural and socioeconomic factors are drivers of land use change. The natural factors include elevation, slope, and aspect. Digital Elevation Model (DEM) data were obtained by incorporating auxiliary data from ASTER GDEM, ICESat GLAS, and PRISM datasets into STRM data and reprocessing them to a spatial resolution of 30 m. Slope and aspect data were obtained using ArcGIS software to analyze the slope and aspect based on DEM data. Socioeconomic factors included GDP, population, and basic geographic information. The basic geographic information data were the distances from general roads, highways, railways, rivers, cities, and downtowns, which were calculated using the Euclidean distance method. To ensure consistency, the above data were all used in a unified Universal Transverse Mercator (UTM), and the image element sizes were resampled to 1000 m (Table 1).

Table 1. Data sources and descriptions.

Data Type	Data Name	Data Source	Spatial Resolution (m)
Land use data	Land use in 2000, 2010, and 2020	GlobalLand30 dataset (http://www.globallandcover.com/)	30
Natural factors	DEM	NASA DEM (https://www.earthdata.nasa.gov/)	30
	Slope		30
	Aspect		30
Socioeconomic factors	Population	WorldPop dataset (https://www.worldpop.org/)	100
	GDP	Resource and Environment Science and Data Center (http://www.resdc.cn/)	1000
	Distance to general roads	OpenStreetMap (https://www.openstreetmap.org/)	1000
	Distance to highways		1000
	Distance to railways		1000
	Distance to river	National Catalogue Service for Geographic Information (https://www.webmap.cn/)	1000
	Distance to city		1000
	Distance to downtown		1000

2.3. Research Methods

2.3.1. Research Framework

In this study, a coupled model consisting of LEAS and CA based on multiple random seed (CARS) modules of the PLUS model and the carbon module of the InVEST model was constructed to simulate urban expansion in the YRD and its impact on TCS (Figure 2). The overall experimental process was as follows: First, land use data for 2000 and 2010 were input into the PLUS model, and the extracted land use expansion data from 2000 to 2010 were used along with the data of the 11 driving factors to calculate the contribution rate of the driving factors and the growth probabilities of each land use type using the random forest method. Second, the 2000 land use data, growth probabilities of each land use type, transition matrix, neighborhood weights, and land demand derived from the Markov chain were incorporated into the CARS module, and the CA model was applied to simulate the 2010 land use data. The simulation accuracy was compared to that of the FLUS model to verify whether the PLUS model obtained a higher simulation accuracy. The above parameters and adjusted parameters were used to simulate land use under three scenarios in 2030: baseline scenario (BS), cropland protection scenario (CP), and ecological protection scenario (EP). Finally, the past and future TCS and the economic value of carbon sinks were calculated by combining the land use data of different periods and four types of carbon density data using the carbon module of the InVEST model. Urban expansion and the changes in TCS caused by it were then processed, handled, and analyzed using ArcGIS software to obtain the final result.

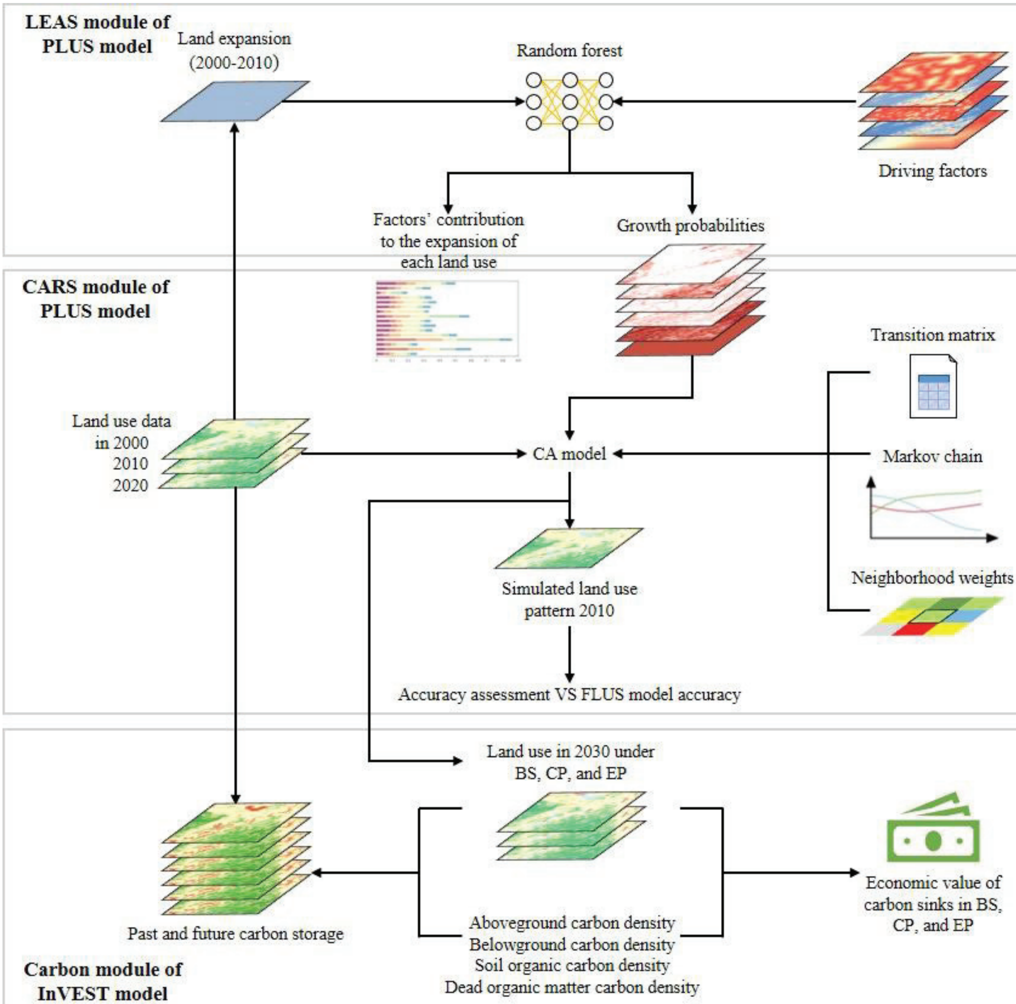

Figure 2. Overall experimental procedure of the study.

2.3.2. Urban Expansion Simulation Based on PLUS Model

The PLUS model is a model for patch generation land-use change simulation developed by the HPSCIL@CUG development team at the China University of Geosciences [24]. It includes two main modules, LEAS and CARS.

The LEAS module calculates the development probability of each type of land use by extracting land-use expansion data using the random forest algorithm, and it analyzes the contribution rate of the drivers of land use expansion [25]. The specific formula for the random forest algorithm is:

$$P_{i,k}^{d}(x) = \frac{\sum_{n=1}^{M} I(h_n(x) = d)}{M} \tag{1}$$

where $P_{i,k}^{d}(x)$ is the probability of growth of land-use type k in spatial cell i, function I is the indicator function of the decision tree, and $h_n(x)$ is the prediction type of the nth decision tree. A d of 1 indicates that there is a transition from other land classes to land class k, and a d of 0 indicates any other land use conversion that does not include land class k.

The CARS module simulates the automatic generation of patches in a spatio-temporal dynamic manner under the constraints of development probabilities of various types of sites combined with random seed generation and threshold-decreasing mechanisms [26]. The formula is as follows:

$$OP_{i,k}^{d=1,t} = P_{i,k}^{d} \times \Omega_{i,k}^{t} \times D_{k}^{t} \quad (2)$$

where $OP_{i,k}^{d=1,t}$ is the integrated probability that spatial cell i is in transition to ground class k at moment t, $\Omega_{i,k}^{t}$ is the domain effect of cell i, which is the proportion of land use components of land class k that are covered in the next domain, and D_{k}^{t} is the effect of future demand on land class k. The future demand for each land-use type was predicted using the Markov Chain module [27]. The parameters of the neighborhood weights were obtained by debugging the model based on previous research results and combining the expansion area share of each land type in the YRD from 2000 to 2010 [17,24]. In the land use transition matrix, 1 means conversion is allowed, and 0 means conversion is restricted (Table 2).

Table 2. Neighborhood weight parameters and transition matrix for the 2010 land use simulation.

Land Use Types	Cropland	Woodland	Grassland	Waterbody	Built-Up Land	Unused Land
Neighborhood weights	0.461	0.032	0.007	0.033	0.467	0.001
Cropland	1	1	0	1	1	1
Woodland	1	1	1	1	1	1
Grassland	1	1	1	1	1	1
Waterbody	1	1	1	1	1	0
Built-up land	1	0	0	1	1	0
Unused land	0	1	1	1	1	1

To ensure that the fitting accuracy of the PLUS model met the research requirements, the same data were input into the FLUS and PLUS models for comparison and validation. The results showed that the fitting accuracy of the PLUS model was higher, with a Figure of Merit (FOM) coefficient of 0.237 compared to 0.178 or the FLUS model, indicating that the use of the PLUS model for land change simulation in the study area is more reasonable than the FLUS model. The obtained kappa coefficient was 93.3%, and the overall accuracy (OA) was 95.6%. Generally, urban land, rural settlements, and others constitute built-up land. Influenced by China's unique national conditions, along with economic development, a large-scale work force is clustered in urban areas, resulting in a rapid outward spreading of urban land, while rural land shows idle or shrinking status. Therefore, for the convenience of model simulation, all construction land was considered urban land.

This study referred to the outline of the YRD Regional Integrated Development Plan (2019–2035), YRD City Cluster Development Plan (2015–2030), YRD Regional Ecological and Environmental Co-protection Plan (2021–2035), and previous related studies [13,19] to set up three future scenarios: (1) BS: Based on the important parameters simulated in 2010, the land use pattern of the YRD under the historical trend was estimated by combining the land use demand in 2030 obtained from the Markov chain projection (Table 3). (2) CP: Based on the principles of national food security and social stability, guarding the red line of cropland, eliminating urban sprawling development, and improving intensive land use. Therefore, the transfer probability of cropland to built-up land was reduced by 30% compared to BS, and this was added to cropland. (3) EP: The YRD is not only the leading economic and social development in China but is the pioneer area for ecological protection. After more than 40 years of sloppy development methods, environmental pollution and ecological damage are serious, and the YRD urgently needs to promote sustainable economic development by transforming land use (protecting ecological land) and adjusting the corresponding parameters. Under the EP, the transfer probability of cropland to built-up land was reduced by 30% compared to CP, and the reduction was added to the conversion of cropland to woodland. The transfer probability of grassland and woodland to built-up land was reduced by 40% compared to CP, and this was added to grassland and woodland, respectively.

Table 3. The number of demand for each land use type in different scenarios in the YRD in 2030 (km^2).

Scenario	Cropland	Woodland	Grassland	Waterbody	Built-Up Land	Unused Land
BS	163,597	99,917	10,870	23,673	49,688	255
CP	164,664	100,250	10,683	23,098	49,045	260
EP	164,092	101,669	11,199	23,347	47,433	260

2.3.3. TCS Estimation Based on InVEST Model

The InVEST model provides a scientific basis for decision makers to weigh the benefits and impacts of human activities by simulating changes in the quantity and value of ecosystem services under different land cover scenarios [11]. The carbon module can estimate TCS based on LULC data, which can generally be divided into four basic carbon pools: aboveground carbon storage (AGC), belowground carbon storage (BGC), soil organic carbon storage (SOC), and dead organic matter carbon storage (DOC). The calculation formula is as follows:

$$S_{total} = S_{above} + S_{below} + S_{soil} + S_{dead} \tag{3}$$

where S_{total} is the total TCS (Tg=10^6 t), and S_{above}, S_{below}, S_{soil} and S_{dead} are AGC, BGC, SOC, and DOC, respectively.

Previous studies have shown that carbon density within a region varies significantly by land type [11,24,28,29]. Therefore, this study developed an LCRV carbon density measurement method. In this method (1) "Literature" refers to the collection of national level soil organic carbon density data through the literature; (2) "Correction" means to use the carbon density correction formula to modify the data to the actual soil organic carbon density in the YRD; (3) "Ratio" refers to the measurement of the remaining three carbon densities (aboveground carbon density, belowground carbon density, and dead organic matter carbon density) in the YRD with the help of carbon pool biomass ratio-carbon conversion rate [30–32]; (4) "Verification" refers to the selection of data (273 sampling points) from the "dataset of carbon density in Chinese terrestrial ecosystems (2010s)" created by Xu et al. [33] in the same latitude and longitude location as the YRD to verify the four types of carbon density, of which the results showed that the measured carbon density data were within their range and consistent with the regional reality (Table 4). The soil organic carbon density correction equation and carbon pool biomass ratio-carbon conversion rate equation were as follows:

$$C_{\rm sp} = 3.3968 \times MAP + 3996.1 \tag{4}$$

$$K_{sp} = C_{sp}^1 / C_{sp}^2 \tag{5}$$

$$C_{tc} = C_{c\_above}/0.157 = C_{c\_below}/0.103 = C_{c\_soil}/0.72 = C_{c\_dead}/0.02 \tag{6}$$

$$C_{\rm tW} = C_{W\_above}/0.217 = C_{W\_below}/0.043 = C_{W\_soil}/0.72 = C_{W\_dead}/0.02 \tag{7}$$

$$C_{\rm tg} = C_{g\_above}/0.118 = C_{g\_below}/0.142 = C_{g\_soil}/0.72 = C_{g\_dead}/0.02 \tag{8}$$

$$C_{\rm tw} = C_{w\_above}/0.025 = C_{w\_below}/0.045 = C_{w\_soil}/0.9 = C_{w\_dead}/0.03 \tag{9}$$

$$C_{\rm tb} = C_{b\_above}/0.175 = C_{b\_below}/0.035 = C_{b\_soil}/0.79 \tag{10}$$

$$C_{\rm tu} = C_{u\_above}/0.217 = C_{u\_below}/0.043 = C_{u\_soil}/0.72 = C_{u\_dead}/0.02 \tag{11}$$

where C_{sp} is the soil organic carbon density (t/hm^2) obtained by correcting the average annual rainfall; K_{sp} is the soil organic carbon density correction coefficient; MAP is the average annual rainfall (mm) of 628, 640.1, 649, 1201, and 1283.403 mm for China, Beijing, Shaanxi, Wuhan, and YRD, respectively; C_{tc}, C_{tW}, C_{tg}, C_{tw}, C_{tb}, and C_{tu} are the total carbon densities of cropland, woodland, grassland, waterbody, built-up land, and unused land, respectively; and C_{above}, C_{below}, C_{soil}, and C_{dead} are the aboveground, belowground, soil, and dead organic matter carbon densities, respectively, for each type of land use.

Table 4. Carbon intensity of each land use type in the YRD (t/hm^2).

Land Use Types	Aboveground Carbon Density	Belowground Carbon Density	Soil Organic Carbon Density	Dead Organic Matter Carbon Density	Total Carbon Density
Cropland	20.329	13.423	93.467	2.596	129.815
Woodland	43.151	8.622	143.371	3.983	199.127
Grassland	18.149	21.772	110.550	3.071	153.542
Waterbody	1.910	3.437	68.746	2.292	76.385
Built-up land	14.548	2.910	65.675	0.000	83.133
Unused land	14.249	2.847	47.342	1.315	65.753

3. Results and Discussion

3.1. Dynamic Evolution of Urban Land Expansion and TCS in the YRD from 2000 to 2020

From 2000 to 2020, the YRD experienced large-scale urbanization acceleration, which was most evident in the riverine and coastal cities (Figure 3I). The urban land area of the YRD increased from 30,138 km^2 (8.660% of the total area of the YRD) in 2000 to 36,929 km^2 in 2010 and 47,138 km^2 (13.545% of the total area of the YRD) in 2020, an increase of 0.564. The expansion of urban land accelerated significantly throughout the study period, with an increase of 6791 km^2 from 2000 to 2010 (average annual growth rate of 2.053%) and 10,209 km^2 from 2010 to 2020 (average annual growth rate of 2.471%). Shanghai's urban land area increased from 1397 km^2 (20.406% of Shanghai's total area) in 2000 to 3000 km^2 (43.821% of Shanghai's total area) in 2020, and the expansion of the urban land area occupied almost 1/4 of the total urban area. The urban land areas of Suzhou, Nantong, and Nanjing increased by 1397, 722, and 714 km^2, respectively, with average annual growth rates of 4.355, 4.533, and 2.668%, respectively.

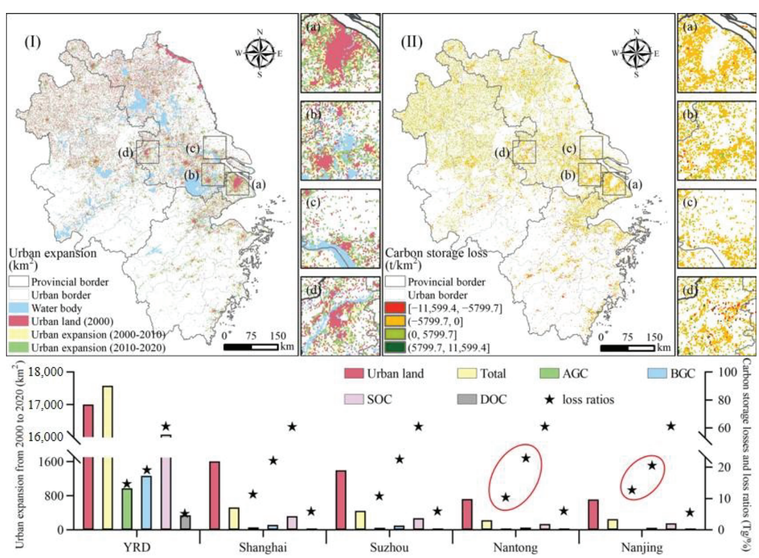

Figure 3. Urban expansion in the YRD and the resulting loss of TCS from 2000 to 2020: (**I**) urban expansion, (**II**) loss of TCS, (**a**) Shanghai, (**b**) Suzhou, (**c**) Nantong, (**d**) Nanjing.

Urban expansion leads to increasing TCS losses, most of which occur in soil (Figure 3II). From 2000 to 2020, the YRD lost 90.189 Tg of TCS. Among the four carbon pools, SOC decreased by 55.13 Tg, accounting for 61.127% of TCS loss, while AGC, BGC, and DOC decreased by 13.208, 17.216, and 4.635 Tg, accounting for 14.645, 19.089, and 5.139% of TCS loss, respectively. Shanghai's TCS declined by 7.149 Tg, accounting for 7.927% of the TCS loss in the YRD. The TCS loss in all four carbon pools was higher than that in the remaining three case areas. Heterogeneity was observed in the proportion of TCS lost from the four carbon pools in different regions. Nanjing's TCS decreased by 3.437 Tg, which was slightly larger than that of Nantong (3.112 Tg). The proportion of AGC loss in Nanjing (12.656%) was higher than that in Nantong (10.312%), whereas the proportion of BGC loss in Nanjing (20.502%) was lower than that in Nantong (22.812%). This stems from the fact that different types of land have been transformed into urban land during urban land expansion. Nanjing encroached on a large amount of woodland in the process of urban land expansion, resulting in increased AGC loss. In contrast, Nantong converted a large area of water bodies into urban land, resulting in increased BGC loss.

3.2. Simulation Projections of Land Use and TCS in the YRD in 2030 under Different Scenarios

Under the BS, the rates of urban expansion and TCS loss in the YRD declined significantly (Figure 4I,II). Under this scenario, the urban land area of the YRD in 2030 was 49,688 km^2 (14.278% of the total area of the YRD), showing an average annual growth rate of 0.528% from 2020 to 2030. Compared to 2000–2020, the loss of TCS slowed to 13.194 Tg, among which the loss of SOC was the most serious, accounting for 62.271% of the total TCS reduction. In contrast, the loss of DOC was the lowest at 0.699 Tg, accounting for only 5.298% of the loss. The rate of land expansion slowed in all cities, with Shanghai, Suzhou, Nantong, and Nanjing increasing their urban land areas by 53, 48, 41, and 87 km^2, respectively. Nanjing had a relatively larger urban land expansion area, and will lose much more TCS than the other three cities in 2030, at 0.493 Tg. AGC, BGC, SOC, and DOC decreased by 0.081 Tg, 0.074 Tg, 0.313 Tg, and 0.025 Tg, respectively.

Compared to BS, the rates of urban expansion and TCS loss were further reduced under CP (Figure 4III,IV). The urban land area of the YRD in 2030 is expected to be 49,045 km^2 (14.093% of the total area of the YRD), with an average annual growth rate of 0.397% from 2020. Ecosystem function degradation would be mitigated in this scenario, with only 8.909 Tg of TCS lost. For the four carbon pools, the proportion of TCS loss was similar to that under BS and was, from highest to lowest, SOC (61.814%), BGC (20.462%), AGC (12.044%), and DOC (5.68%). The urban land expansion area of Shanghai decreased significantly, which was slightly higher than that of Nantong but significantly lower than that of Suzhou and Nanjing. Shanghai's urbanization process began early and developed rapidly. After 2020, the land types were mainly built-up land and cropland, with little change in urban land use, as cropland protection limited encroachment on cropland. The TCS loss in Shanghai in 2030 is 0.135 Tg, and the losses of the four carbon pools are only 0.01, 0.032, 0.084, and 0.009 Tg, respectively.

Under EP, the YRD showed the lowest loss of urban expansion area and TCS (Figure 4V,VI). The urban land area of the YRD expanded to 47,433 km^2 (13.63% of the total area of the YRD) by 2030, with an average annual growth rate of 0.062% from 2020 to 2030. The urban expansion area was significantly reduced, and the TCS loss was only 1.17 Tg. Moreover, owing to the strict control of the conversion of ecological land, such as woodland and grassland, to urban land, the proportion of AGC loss in the EP decreased by 5.414% compared to that under BS. Suzhou and Nantong did not experience significant urban expansion, growing by only 10 and 0 km^2, respectively. The loss of TCS in Suzhou in 2030 was 0.02 Tg, with AGC increasing by 0.003 Tg due to the conversion of only a small amount of cropland and waterbody to urban land and BGC, SOC, and DOC experiencing losses of 0.006, 0.015, and 0.002 Tg, respectively.

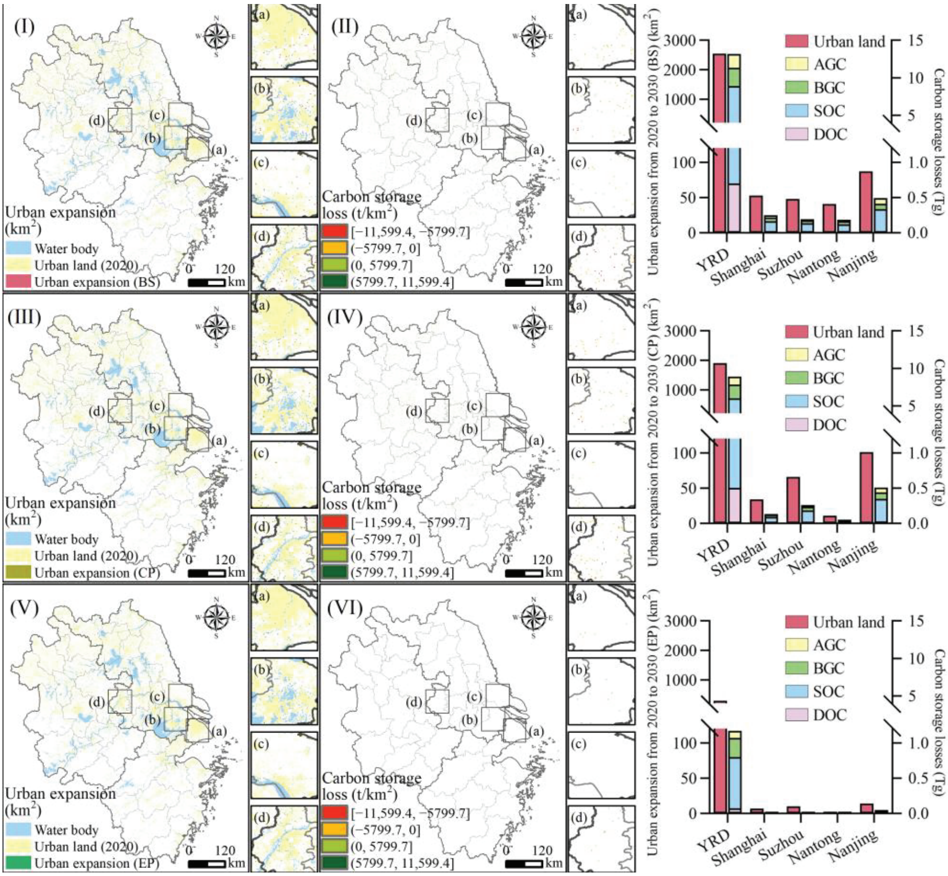

Figure 4. Simulation of urban expansion in the YRD under three scenarios and its resulting loss of TCS: (**I**) urban expansion under BS, (**II**) loss of TCS under BS, (**III**) urban expansion under CP, (**IV**) loss of TCS under CP, (**V**) urban expansion under EP, (**VI**) loss of TCS under EP, (**a**) Shanghai, (**b**) Suzhou, (**c**) Nantong, (**d**) Nanjing.

3.3. Main Reasons for the Decline of TCS during Urban Expansion in the YRD

To analyze the main causes of TCS loss during urban expansion in the YRD, this study used the LEAS module of the PLUS model and the land-use transfer matrix to explore the drivers of urban land growth and the main causes of TCS loss, respectively.

The slope, transportation arteries (general roads, highways, and railways), and rivers were the main drivers of urban expansion in the YRD (Figure 5). This study used the LEAS module to reveal the potential drivers of urban expansion and the strengths of their contributions. Slope had the greatest impact on urban expansion, with a contribution of 0.231, followed by distance to general roads, DEM, distance to highways, distance to railways, and distance to rivers, with contributions of 0.166, 0.165, 0.136, 0.114, and 0.112, respectively. These results indicated that additional urban land was mainly distributed around transportation arteries with gentle topography and adjacent to the old city, which was verified by Dadashpoor et al. [34] and Liang et al. [24], who studied the Tehran Metropolitan Region (TMR) and Wuhan, respectively. Osman et al. [35] divided the Giza Governorate of the Greater Cairo Metropolitan Region (GCMR) into three parts according to the stage of urbanization and used a questionnaire to indicate that economic incentives, population increases, and administrative functions that were the most influential forces for urban expansion in the central, northern, and southern parts of the city, respectively.

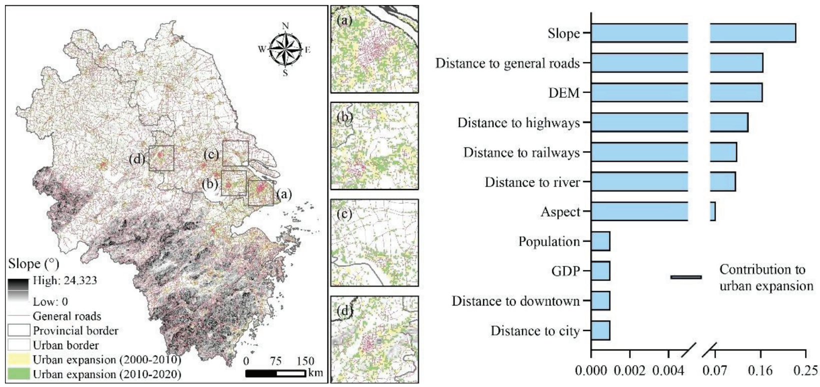

Figure 5. Contribution of drivers such as slope and general roads to urban expansion: (**a**) Shanghai, (**b**) Suzhou, (**c**) Nantong, (**d**) Nanjing.

Cropland occupation was the main cause of TCS loss in the YRD region (Table 5). The urban land transfer matrix revealed that the amount of urban land transfer in the YRD from 2000 to 2010 was small, but that from 2010 to 2020 was significant. From 2000 to 2020, 15,525 km^2 of cropland was converted to urban land, accounting for 91.324% of the new urban land. This directly led to a TCS loss of 72.474 Tg, accounting for 81.156% of the total TCS loss, which differed from the 63.73% reported by He et al. [11] in Beijing, mainly because of the different proportions of each land type from those in the YRD. In addition, 1352 km^2 of woodland and 157 km^2 of grassland were converted to urban land, resulting in TCS losses of 15.682 and 1.105 Tg, respectively. The TCS of the water bodies and unused land remained largely unchanged. The natural resource endowments and socioeconomic development of different countries are heterogeneous; therefore, the carbon density and land use transfer are different. Li et al. [36] and Hutyra et al. [37] found that deforestation caused 5.0 ± 3.6 and 1.2 t/hm^2 of TCS loss and was the main cause of TCS loss in the Amazon region and Seattle metropolitan area, respectively. Together, these findings show that when urban expansion occurs along the direction of gentle slopes, transportation arteries (general roads, highways, and railways), and rivers, the majority of the occupied land is cropland with a high carbon density, which leads to a serious loss of TCS.

Table 5. Urban land transfer matrix and its TCS changes in the YRD from 2000 to 2020 (km^2/Tg).

Time Period	-	Cropland	Woodland	Grassland	Waterbody	Unused Land
2000–2010	Transfer out volume	9	0	0	20	0
	Transfer in volume	6240	359	42	178	1
	TCS	−29.088	−4.164	−0.296	0.107	0.002
2010–2020	Transfer out volume	16,992	1230	177	1435	19
	Transfer in volume	26,286	2223	292	1259	2
	TCS	−43.386	−11.518	−0.810	−0.119	−0.030

Note: Positive values indicate an increase in TCS and negative values indicate a loss of TCS.

3.4. Practical Implications

Carbon sinks have huge economic benefits and can effectively mitigate the loss of carbon sink value under CP and EP conditions. Similar to She et al. [38] and Carr et al. [39], this study used the InVEST model to assess the loss of economic value of carbon sinks owing to urban expansion in different scenarios. Three important parameters were required for the evaluation process: (1) the social cost of carbon emissions, which, according to

Ricke et al. [40], was set as USD 24/t; (2) the market discount rate of the economic value of carbon sinks, which was set at 10%, as used in the evaluation of the project by the Asian Development Bank [41]; and (3) the interannual rate of change in the social cost of carbon emissions, which was set at 0 with reference to available research results [42]. The results under BS found that the economic value of the carbon sink reduced by USD 315.221 million with an urban land expansion of 2550 km^2 in the YRD; under CP, the area of urban expansion and resulting economic value loss of carbon sink were 1907 km^2 and USD 212.853 million, respectively; and under EP, these values were 295 km^2 and USD 27.955 million, respectively. Therefore, with the slowdown of urban expansion under CP and EP, it is possible to reduce the economic losses from the loss of carbon sinks by USD 102.368 and 287.266 million, respectively.

In the context of global warming, future urban expansion of the YRD will further aggravate the loss of TCS and pose a serious threat to the achievement of China's 'double carbon' target. TCS are highly vulnerable to climate change and human activity [43]. Prietzel et al. [44] found that carbon loss from deep soils due to global warming far exceeds the increase in plant biomass and carbon storage in litter, which causes a decline in total TCS and a further increase in global temperatures. In addition, urban expansion directly affects TCS and indirectly affects anthropogenic carbon emissions [45]. Chuai et al. [46] argued that human activities associated with anthropogenic carbon emissions always make land a carrier. This study measured regional carbon emissions based on carbon emission factors provided by the Intergovernmental Panel on Climate Change (IPCC) and found that urban land is where carbon emissions are most concentrated and intense, and promoting intensive land use can effectively mitigate the greenhouse effect. Since 2017, China's economy has moved to a stage of high-quality development, and ecological environmental protection has received unprecedented attention and has gradually been integrated into all areas and aspects of economic and social development. In 2020, China set a strategic goal of reaching peak carbon emissions by 2030 and achieving carbon neutrality by 2060 [47]. However, the carbon emission effect of future urban land expansion in the YRD will add to the pressure on China to reduce carbon emissions and may undermine the "low carbon city" development concept and China's commitment to the Paris Climate Agreement.

Therefore, there is an urgent need to establish a regional development plan based on ecosystem services. The loss of carbon sinks due to urbanization is not unique to the YRD. Wang et al. [41] found that, under a natural development scenario, Wuhan's urban expansion will result in a direct loss of USD 26.5 million through carbon sink value loss by 2035. At the same time, urban expansion is a serious threat to many other ecosystem services. For example, Yuan et al. [48] found that China's economic development has been highly dependent on increased urban land area and quantified the value loss of five ecosystem services (food production, water conservation, climate regulation, habitat support, and cultural service) during urbanization in China and found a total loss of USD 110.95 billion over the last 30 years. Campbell et al. [49] optimized the land use structure of Maryland, USA to reduce the potential loss of seven ecosystem services from increased population and economic development. Ecosystem services are an important resource for human survival and development, and their socio-cultural value should receive more scholarly attention [50]. However, at present, at both national and individual levels, the awareness of protecting ecosystem services is underdeveloped [30]. Therefore, in future regional planning, we should strengthen the protection of ecological land such as cropland and woodland, insist on the "reduction" of inefficient construction land, and establish the concept of "smart growth" and "compact city".

3.5. Limitations and Future Directions

Dynamic changes in land use refer to changes in land use patterns and utilization levels caused by the interaction of elements in natural and human systems. In this study, 11 types of data, including DEM, slope, GDP, and population, were selected as drivers for simulating the spatial layout of future land use, and multiple models were used for comparison and validation to select the best-fitting results. Despite the high accuracy of the simulation results, the influence of policy factors, such as ecological protection red lines and urban development boundaries, on land use change was not considered. Therefore, to further improve the accuracy of land use simulations, relevant policy factors should be incorporated into the driving factor system in the future. In addition, subsequent studies using remote sensing data with a higher spatial resolution are needed.

The InVEST model is widely used to estimate the functions of ecosystem services (e.g., water production and biodiversity) and their economic value. It has been commonly applied by many researchers worldwide for its advantages of easy operation and visual representation, and it has promoted the progress of research on ecosystem carbon storage services; however, it has some limitations. The model oversimplifies the carbon cycle principle by assuming that carbon density is homogeneous and constant, ignoring that carbon density changes dynamically over time and as the environment changes [51]. Therefore, to improve the accuracy of the assessment results, future studies should supplement and correct carbon density using multi-year and continuous field observation data, and a more detailed land-use classification system should be adopted to compensate for the lack of spatial heterogeneity within land-use types [45].

4. Conclusions

Based on the coupled model of PLUS and InVEST, this study combined the scenario simulation method, LCRV carbon intensity measurement method, and land-use transfer matrix to simulate past and future urban expansion in the YRD and its impact on TCS. An attempt was made to construct a unified accounting standard for carbon density on a large scale, and the drivers and economic values of TCS changes during urban expansion were explored in depth. The main findings were as follows: (1) The urban land area of the YRD expanded 0.564 times from 2000 to 2020 (approximately 17,000 km^2), and the expansion rate accelerated significantly with time, with an average annual growth rate of 2.053% from 2000 to 2010 and 2.471% from 2010 to 2020. Meanwhile, the TCS declined significantly, with an annual average reduction of 4.509 Tg. Of the TCS losses, 61.127% occurred in soil. Land conversion and the loss of TCS were particularly prominent in riverine and coastal cities with economic and population centers (Shanghai, Suzhou, Nantong, and Nanjing). (2) The rates of land expansion and TCS loss in the cities of the YRD decreased to different degrees under all three scenarios. Under BS, the urban expansion area was the largest at 2550 km^2 and the associated TCS loss was 13.194 Tg. EP had the smallest urban expansion area (295 km^2) and lowest TCS loss (1.17 Tg). (3) The slope, transportation arteries (general roads, highways, and railways), and rivers were the main drivers of urban expansion in the YRD, with a combined contribution of 0.924. The main reason for the loss of TCS was the encroachment of croplands by urban land. From 2000 to 2020, 91.324% of the urban expansion land originated from croplands, which directly led to a TCS loss of 72.474 Tg. Carbon sinks have huge economic benefits, and under CP and EP, the economic losses from the loss of carbon sink value can be reduced by USD 102.368 and 287.266 million, respectively, compared to that under BS.

Although we studied the impact of urban expansion on TCS in the YRD using model simulation methods, there were some shortcomings in the study. The effects of policy factors on land-use changes and the fact that carbon density changes dynamically with time and geographical environment changes were ignored. In future studies, policy factors, such as ecological protection red lines and urban development boundaries, should be included in the driving factor system to improve the accuracy of land use simulation. Simultaneously, carbon density should be supplemented and corrected using multi-year and continuous field observation data. These will be explored by land-use planners and environmental science scholars around the world because feeding this information back to urban planning and management departments will help future sustainable urban development.

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Article

Spatial and Temporal Interaction Coupling of Digital Economy, New-Type Urbanization and Land Ecology and Spatial Effects Identification: A Study of the Yangtze River Delta

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Abstract: In the digital era, the contradiction between regional urban development and land ecological protection is still prominent. Clarifying the relationship and internal interaction logic among digital economy (DE), new-type urbanization (NU), and land ecology (LE) is of great significance to the region's sustainable development. Based on theoretical analysis, this study examines the relationship among DE, NU, and LE in the Yangtze River Delta through spatial analysis and empirical test with the city data from 2011 to 2020. The study found that: (1) The overall development level of DE–NU–LE in the Yangtze River Delta shows a steady upward trend, the development level of DE and NU lags behind LE, and the convergence trend among them gradually strengthened. (2) The DE-NE-LE and the coupling coordination have different and complex spatial and temporal dynamic evolution characteristics. The ability for coordinated development is enhanced continuously, which presents a typical pattern of "high in the east and low in the west". (3) The DE has a lasting role in promoting the development of the NU and LE, while the support and stimulation of NU and LE for DE needs to be strengthened. The relationship between the NU and LE shows a mutually restricted trend. (4) The DE has a significant "siphon effect". While NU and LE both have significant positive spatial spillover effects, which can promote the coordinated development of surrounding cities. This study deepens the understanding of DE–NU–LE coordinated development, and provides a new perspective for sustainable urban development and alleviating land conflicts.

Keywords: land ecology; digital economy; urbanization; land conflict; coupling coordination

1. Introduction

Land is one of the most important foundations for human survival and development and is an irreplaceable material wealth of human society. The healthy and safe development of LE is not only the environmental foundation for regional development but also an important guarantee for sustainable development. However, since the industrial revolution, with accelerated urbanization and industrialization, the social and economic development has been rapid. Land resources development and protection have been greatly impacted and affected, and the competition for ecological space has been frequent. In this context, the contradiction between humans and land caused by rapid economic development and urbanization has become increasingly prominent, and regional sustainable development is facing severe challenges [1]. As China's development enters a new era, the construction of ecological civilization is elevated to a national strategy. How to coordinate the development of LE and urbanization is a popular proposition in current urban development. To this end, *the 14th Five-Year Plan for the Implementation of New-Type Urbanization* emphasizes the comprehensive planning of national land space. The ecological protection red lines and urban development boundaries have been defined and implemented to improve the quality and stability of the ecosystem. At the same time, digital technology application scenarios are enriched to improve urban governance and land management. Similarly, *the National Adaptation Strategy for Climate Change 2035* mentions promoting the construction of digital twins for the river basins. Additionally, the digital platform will be established for ecological governance technologies to strengthen early warning monitoring and emergency response capabilities for water and land resources. It can be seen that the DE and its related technologies have become an important driving force for the high-quality development of Chinese cities. Therefore, coordinating the relationship among the development of DE, NU, and the protection of LE has great practical significance for sustainable regional development and the construction of ecological civilization.

The related studies around DE, NU, and LE have received extensive attention from scholars. Most current literature only discusses the development and influence of a single system, and the research on the relative relationship between multiple systems is weak. Especially, less attention is paid to the coupling mechanism and coordinated development among the DE, NU, and LE. First of all, from the related research on DE, the DE concept has not yet been unified [2]. The term "digital economy" can be traced back to 1996, when it was first proposed by Tapscott Don [3], an American businessman. For a long time, scholars have further discussed and enriched the concept and connotation of the DE. As Lane [4] pointed out, the DE refers to the convergence of computing and information technology on the Internet and the resulting flow of information technology has triggered the electronic transformation of business. Later, Moulton [5] believed that the information technology industry and its related technologies, digital transactions of goods and services, and tangible commerce, retail, and related investments supported by digital technologies are all part of the DE. Then, Dahlman [6] mentioned that the DE is the amalgamation of economic and social activities with digital information as the main production factor and supported by information technologies such as big data and cloud computing.

In terms of social development, the DE plays a multi-tiered driving role. On the one hand, the DE can promote benign adjustment at the micro level of cities by improving resource misallocation [7], enhancing urban total factor productivity, and promoting industrial innovation [8,9]. On the other hand, the DE also plays a positive role in macro-environmental development such as green and low-carbon development [10], urban and rural coordination [11], inclusive growth [12,13], and economic and financial inclusion [14,15].

Second, from the research related to NU, the term "new-type urbanization" originates from China and is an urbanization path with distinctive Chinese characteristics. Hence, the current research on NU is also basically focused on China. Compared with traditional urbanization, which is mainly based on land development, the NU, which upholds the core connotation of being people-oriented is more intensive, efficient, harmonious, and sustainable [16]. Similarly, the influence of NU is also multi-faceted for economic and social development. The development concepts of green, low-carbon, and recycling are conducive to reducing environmental pollution [17], and improving energy utilization efficiency [18,19]. The NU shows significant ecological benefits [20], which accelerates urban green transformation. The core connotation of being people-oriented, puts more emphasis on human development and has greater inclusiveness and universality, which facilitates the stable transfer of rural labor and improves the income level of rural residents [21]. Under the overall framework of urban-rural integration development, bridging the income gap between urban and rural is conducive to accelerating rural revitalization and enhancing the happiness of urban and rural residents [22,23]. However, it is worth noting that although NU has the ecological effect of "reducing pollution and increasing efficiency", it also poses a great challenge to land resources. Against the background of decreasing cultivated land, inputs of high-carbon production materials such as chemical fertilizers and pesticides are on the rise to ensure food production. The overuse of chemical fertilizers can cause soil acidification [24], nutrient imbalance in soils, and destroy soil biodiversity [25], which puts pressure on the sustainability of the land. Although pesticides can prevent and mitigate the effects of pests, they also further amplify the risk of soil and water pollution [26]. In addition, large-scale infrastructure construction tends to cause some land ecological problems such as soil degradation and erosion [27], etc. Therefore, how to find a balance between the construction of NU and the protection of LE is a real problem for the current sustainable development of the region.

Finally, from the relevant studies on LE, the land ecosystem is a complex dynamic system formed by the interaction of interdependent natural elements and human activities on the Earth's surface [28]. From the above definition, first of all, land ecosystem includes the continuous distribution of elements on the Earth's surface, such as agricultural land, grassland, forest, etc., which are the main bearers of resources [29]. As part of the ecosystem, land ecology is more focused on the condition of the land. It is the basis for land use planning and structural layout. Secondly, the LE considers the human–land relationship and the derived ecological values [30]. Through reasonable input and transformation of the land, it can cause LE to develop in a more efficient direction and to obtain the corresponding economic and living benefits [31,32]. Conversely, predatory human activities on the land can lead to ecological degradation of the land [33]. Finally, the LE is an open and dynamic system, and its condition is not static. On the one hand, the LE can resist the adverse changes of the environment with the self-regulating and compensatory effects [34]. However, its effectiveness is limited. On the other hand, external shocks such as biological activities, landscape transformation, climate change, and natural disasters can have certain impacts on LE. The sustainable development of land resource use and social economy are further affected. From the relevant studies, compared with studies on the ecological environment, existing research on LE is limited. Researches on LE mainly focus on land ecological security assessment [35,36], land ecological efficiency [37], land resources [33,38], land use [39], and land sustainable development [40]. For instance, Feng [41] systematically assessed the land ecological safety in Ningbo, a coastal city in eastern China, and summarized its temporal characteristics. Then Yu [42] used the slacks-based measure-undesirable (SBM-UN) model to study the land use efficiency of urban agglomerations in China and further analyzed its driving factors. In addition, some scholars have also studied the relationship between urbanization and land. Although the conclusions are different, the contradiction between urbanization and land is particularly common [40,43,44].

To sum up, the synergistic development of DE, NU, and LE is a necessary path for Chinese cities to move toward high-quality development. Nevertheless, the development foundations of DE, NU, and LE in Chinese cities are quite different at present, and the development levels are uneven. Furthermore, the multi-system coordination mechanism is not yet clear. Given this, this paper takes the Yangtze River Delta as a study area to explore the coordinated development mechanism of subsystems. The spatial and temporal evolution characteristics of subsystems coupling coordination development are revealed by the coupling coordination model, which is modified. Finally, the interaction mechanism and spatial effects of subsystems are identified with the panel vector autoregression (PVAR) model and spatial econometric model. The contributions and innovations of this paper mainly lie in the following three aspects: (I) In terms of theoretical innovation, this paper incorporates DE, NU, and LE into a unified analytical framework and systematically discusses the internal logic and coupling mechanism of subsystems. The relevant achievements can be enriched, which fills a partial vacancy in the research on the linkage development mechanism of DE, NU, and LE. (II) In terms of empirical evidence, this paper reveals the different evolutionary characteristics of DE, NU, and LE in the Yangtze River Delta and further explains the reasons behind them. It clarifies the spatial and temporal evolution characteristics of the subsystems and the coupling coordination development. (III) In terms of path innovation, this paper explores the spatial effect of DE, NU, and LE, and provides a spatial perspective for promoting the coordinated development of DE, NU, and LE.

The rest of the sections in this paper are arranged as follows: Section 2 is the portrayal of the coupling mechanism. Section 3 is the introduction of the study area, methods, and data resources. Section 4 is the analysis of the empirical results. Section 5 is the identification of the interaction mechanisms and spatial effects. Section 6 is the conclusions and suggestions.

2. The Coupling Mechanism

Based on the existing studies, this paper constructs a mechanism analysis framework for the coupling of DE, NU, and LE according to the interaction relationship among the three (Figure 1).

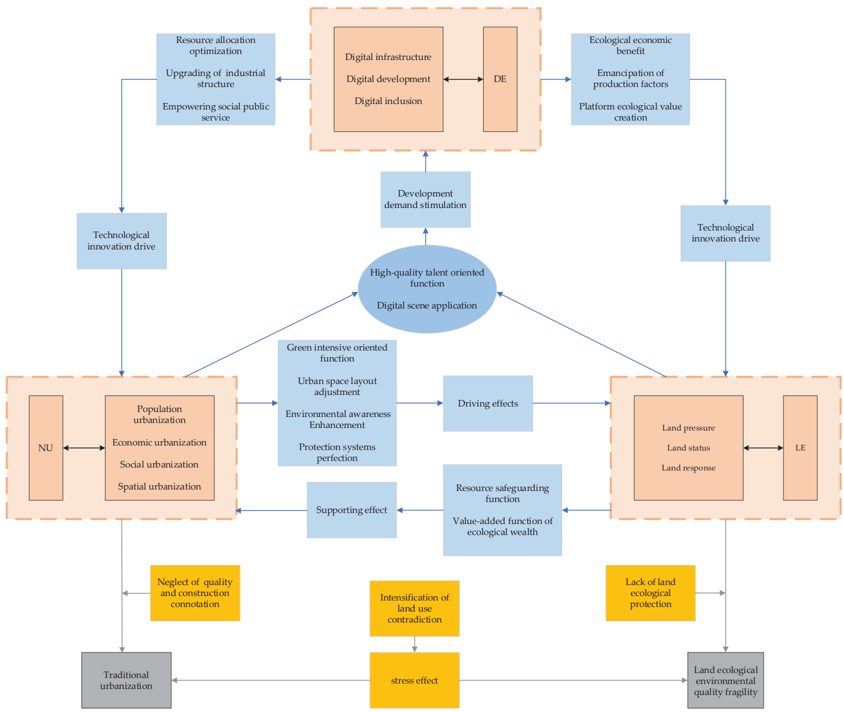

Figure 1. The coupling mechanism of DE–NU–LE.

Science and technology are the first productive forces of socio-economic development. The DE, mainly supported by information technologies such as artificial intelligence, big data, and the Internet [45], presents obvious new technological characteristics. The resulting series of technological and industrial innovations has become a powerful driving force for the development of NU and LE. Specifically, the driving effect of DE on NU is mainly manifested in three aspects: (I) The DE has an optimization effect on resource allocation [7]. Digital technology has changed the traditional method of resource allocation. The industrial changes and technological innovation in cities are effectively promoted by rapid flow and utilization efficiency improvement of production resources. It accelerates local urbanization [46] and enhance urbanization efficiency [47]. (II) The DE facilitates industrial upgrading and provides new options for bridging the income gap. The technological advantage of DE further generates new industries and transforms traditional industries to provide employment and training opportunities for more people [10,48]. The residents' income will rise because of working, which could reduce the urban-rural income gap [11] and enhance residents' well-being [49]. The experience of developed regions shows that the rational flow of resource factors and increase in employment will be more conducive to improving the quality of urbanization [50]. (III) Digital technology and its applications can empower the construction of social public services and provide a new path to achieve equalization of public services [51]. The improvement of public service quality is the core content of NU, its improvements such as medical care, transportation, and education plays an important role in promoting the happiness of residents' lives. The development of DE is conducive to accelerating the digital transformation of urban public services, improving the efficiency of public affairs, and enhancing the credibility of government data. Meanwhile, high-quality resources in healthcare and education can be digitally disseminated. The process of equalization of public services is accelerated through digital dissemination to cover and influence more places and people.

In terms of LE, there are good performances of DE in enhancing the ecological quality of land: (I) the ecological and economic benefits that the DE itself possesses. On the one hand, the DE has good ecological benefits in the process of promoting the transformation of traditional industry. It can effectively reduce industrial pollution emissions [52], improve energy efficiency [53], and achieve low-carbon transformation [54], which plays an important role in the overall protection of the ecological environment. On the other hand, the DE can effectively promote economic growth [55], thus fully guaranteeing the investment of funds for ecological protection and restoration. (II) The emancipation effect of DE on production factors. Firstly, the DE uses digital information as the main production factor, which has the characteristics of being clean, intensive, and efficient [10]. Secondly, the DE can reduce the cost of land production factors and improve agricultural efficiency [56]. The application of digital technology in the field of agricultural production can achieve savings in labor, water, land, and fertilizers [57,58]. The digital liberation of agricultural productivity provides greater scope for replenishing degraded land, enhancing land resilience, and achieving rational landscape planning and management [59]. (III) The DE has the role of platform ecological value creation [60]. On the one hand, the government-led digital platform can form a closely linked ecological collaborative governance model; and achieving overall regional ecological protection and rational planning through digital monitoring, management, and precise governance. On the other hand, an enterprise and market-led platform can effectively utilize the timeliness and convenience of the information network. The land ecological value can be increased by transformation of land productivity to economic benefits on platforms such as e-commerce. Accordingly, NU and LEs will continue to attract high quality talent for their own development needs, which accumulates human capital for the development of DE. With the in-depth development of NU and LE, the demand for quality improvement will reverse stimulate the development of related technologies [61]; also creating new development opportunities and application scenarios for digital development. The application of digital ecological governance, digital government, digital twin cities, and other related technologies is not only a result of the development of the DE itself, but also an inherent requirement of NU and LE.

In terms of the interaction between NU and LE, the driving effect of NU on LE is mainly reflected in three aspects: (I) The NU has intensive green oriented function [16]. The green, intensive, intelligent, and sustainable development concept of NU places more emphasis on the coordinated development between cities and the ecological environment rather than mutual trade-offs [37]. Under the guidance of relevant concepts, the predatory land management mode is gradually abandoned. Through the active guidance of the government, the industrial development model with high pollution, high emissions, and high consumption is in a transform position. Eventually, the intensive use of land is realized through the transformation of urban industry and operation mode. (II) The NU puts forward more strict and precise requirements on urban spatial layout. It clearly limits the urban development boundary, and the restoration space can be retained for land. (III) The continuous progress of NU is accompanied by the improvement of living standards. The individual and collective awareness of environment protection is strengthening with rapid growth of public demand for high-quality urban space and land security. The government also strengthens the protection of LE and accelerates the perfection of the relevant protection systems in order to meet the growing ecological needs of the public.

A good land ecological environment is the foundation for the smooth progress of NU. It is mainly reflected in two aspects: (I) The LE has the function of resource guarantee [29]. Land is scarce, and land that can be used for production and housing is even scarcer. In order to realize the sustainable development of land resources, the protection of LE is needed. The safe development of LE, especially food security, is the material guarantee and spatial basis for human survival and urban development. (II) The LE has a wealth-adding function [62]. It provides new possibilities for dealing with the problem between urban development and land conservation. Firstly, through the marketization and valorization of land productivity, especially agricultural products, the advantages of land resources are converted into ecological product advantages. Secondly, the accumulation of land ecological assets is realized through ecological compensation and green financial products such as carbon finance. Ultimately, the mutual integration of ecological capital and urban development can be realized. Therefore, NU and LE complement each other and their coordinated development is an effective way to achieve sustainable development. However, due to the lesser attention paid to the quality of development and the core meaning of the NU, urban construction is prone to take the old path of being extensive. The over-exploitation of land resources and the growing demand for land will further squeeze the ecological space of land, intensify land conflicts, and even form a mutual stress effect [43,44].

3. Study Area, Materials and Methods

3.1. Study Area and Data Sources

According to *the outline of the integrated regional development of the Yangtze River Delta* issued in 2019, the scope of the Yangtze River Delta includes Jiangsu Province, Zhejiang Province, Anhui Province, and Shanghai City, with a total of 41 cities in the whole area. As of the end of 2020, the Yangtze River Delta accounts for 16.79% of the country's population and produces 24.09% of the country's GDP on 3.7% of the country's land area. At present, the Yangtze River Delta has become one of the regions with the most developed economic development in China. It is an important leading area and demonstration area for the development of DE, the construction of NU, and ecological civilization in China. The Yangtze River Delta region has modern port groups and airport groups, high density traffic arteries, basic connectivity of major infrastructure, and relatively balanced development of public services. The interactive mechanism of ecological protection and the pattern of coordinated urban and rural development are gradually taking shape. In terms of DE development, the Yangtze River Delta region has obvious advantages in technological innovation. In 2020, the total digital economy will reach CNY 10.83 trillion, about USD 1.57 trillion, accounting for 44.26% of the Yangtze River Delta's GDP, and its development level ranks on the top-tier for China.

The data used in this paper are mainly from *the China City Statistical Yearbook*, *China City Construction Yearbook*, provincial and municipal statistical yearbooks, local statistical bulletins, and the EPS database. The PM2.5 data are obtained from the Surface PM2.5 Dataset of the Atmospheric Composition Analysis Group at Washington University in St. Louis. The data on digital financials are obtained from the China Digital Finance Inclusion Index measured by the Digital Finance Research Center of Peking University in cooperation with Ant Financial Services Group (https://www.dfor.org.cn/, accessed on 19 January 2023). The missing values of the necessary data are supplemented by linear average and interpolation.

3.2. Study Methods

3.2.1. Indicator System Construction

Based on the discussion of the coupling mechanism above, this paper makes a comprehensive evaluation of DE, NU, and LE from multiple dimensions. The specific construction methods and indicators are as follows.

The DE, as a new economic form with data resources as production factors and digital technology as the main mode of production, has obvious technical characteristics. Additionally, it is based on information technology, with Internet technology as the carrier. In terms of measurement, most scholars currently select representative indicators from different dimensions to reflect its information construction and the foundation of the Internet, and the development of related digital industries [55,63]. Therefore, following the ideas mentioned above, this paper makes a comprehensive assessment of the DE development from three dimensions: digital infrastructure, digital development, and digital inclusion, where digital infrastructure can reflect the material conditions and market potential of digital development, and usually be measured by internet penetration rate and mobile phone usage. Digital development can represent the development vitality of the DE, which is mainly measured by digital practitioners and telecommunications business volume. Additionally, digital inclusion reflects the degree of integration between digital technology and social economy, which is measured by digital finance inclusion index.

The NU, with distinctive Chinese characteristics, is an inheritance and abandonment of traditional urbanization. It aims to achieve comprehensive human development and attaches importance to the coordinated development of multi-dimensions such as economy, society, space, and population. The construction of an urbanization evaluation system in existing studies has also changed from a single evaluation index measured by urbanization rate to a multi-dimensional comprehensive evaluation system. Additionally, the main features and basic connotations of the NU have been highlighted. Therefore, drawing on the existing research [27,64], and considering the availability and repetitiveness of data, the urbanization of population-economy-society-space is used as the evaluation basis of NU development, where population urbanization emphasizes changes in resident attributes, which mainly include urbanization rate and urban employed population. Economic urbanization is intended to represent the potential of urban economic development, including economic growth rate, residents' income, and the proportion of modern industrial output. Social urbanization emphasizes the improvement of the city's social environment and the popularization of public services, such as public transport, expenditure of science, education, air quality, and social consumption level. Spatial urbanization represents the spatial basis of urban development, which is usually measured by the expansion of built-up areas and space per capita.

As an important part of the ecological environment, The LE puts more emphasis on land carrying capacity, land structure, and land function. At present, there are two main evaluation methods for the LE. One is to start from economic and social benefits, consider creating more economic value with less environmental sacrifice, and use land ecological efficiency to measure the development of LE. The other is to use the index system method to evaluate LE from different dimensions. Xu (2014) evaluated Guangzhou's land ecological security from demand and supply aspects. Chen [31] made a fuzzy assessment of China's land resources based on the pressure-state-response (PSR) framework. Considering the availability and accuracy of prefecture-level city data, this paper conducted a comprehensive assessment of LE in the Yangtze River Delta using the PSR framework. Due to the scarcity of land, the pressure on land mainly comes from population growth, industry development, and land pollution. Therefore, urban population density, agricultural economic efficiency, and land pollutants are used to represent the degree of land pressure. The land status is a comprehensive consideration of land structure, land function, and overall development, which is usually measured by industrial land, green area, food security, soil and water coordination degree, land economic density, and the green development index. The response indicators are positive feedbacks and concerns to changes of LE [35]. Generally, cities with better economic development pay more attention to the governance and protection of the ecological environment. Thus, GDP per capita, pollutant treatment rate, and green coverage area that are a general representation of land restoration are used to measure the land response.

The specific index system is shown in Table 1.

Table 1. Evaluation indicators and weights of DE–NU–LE development in the Yangtze River Delta.

Subsystem Layer	Dimensional Layer	Indicator Layer	CRITI Weights	Entropy Weights	Type
DE	Digital infrastructure	Number of Internet users per 10,000 people	0.0916	0.1776	+
		Number of cell phone subscribers per 10,000 people	0.0808	0.1743	+
	Digital development	Computer services and software practitioners	0.5050	0.2711	+
		Total telecommunications business	0.2452	0.2047	+
	Digital inclusion	Digital finance inclusion index	0.0775	0.1721	+
NU	Population urbanization	Urbanization rate	0.0464	0.0870	+
		The proportion of employees in the secondary and tertiary industries	0.0424	0.0847	+
	Economic urbanization	GDP growth rate	0.0531	0.0853	+
		Disposable income of urban and rural residents	0.0725	0.0908	+
		The proportion of output value of secondary and tertiary industries	0.0394	0.0858	+
	Social urbanization	The proportion of fiscal expenditure on science and education in GDP	0.0903	0.0867	+
		Per capita retail sales of consumer goods	0.0712	0.0910	+
		Urban bus operation volume	0.2174	0.1091	+
		PM2.5	0.0897	0.0874	−
	Spatial urbanization	Per capita built-up area	0.0985	0.0906	+
		The proportion of urban built-up area in land area	0.1791	0.1015	+
LE	Population pressure	Population density	0.0222	0.0674	−
	Industry pressure	Total agricultural output value-added/The area of cultivated land acquired in the year	0.0215	0.0670	−
	Environmental pressure	Fertilizer application per unit sowing area	0.0526	0.0685	−
		Industrial waste gas, wastewater, and waste load per unit of land	0.0331	0.0678	−
	Land structure	The proportion of industrial land area	0.0188	0.0672	−
		Urban per capita green area	0.1715	0.0771	+
		Total water resources/Crop sown area	0.2163	0.0860	+
	Land function	Grain output per unit sown area	0.0659	0.0694	+
		land economic density	0.1679	0.0842	+
	Overall development	Green development index	0.0785	0.0721	+
	Population response	population growth rate	0.0153	0.0668	−
	Industry response	GDP per capita	0.0839	0.0725	+
	Environmental response	The comprehensive utilization rate of general industrial solid waste	0.0270	0.0671	+
		Green coverage rate	0.0256	0.0670	+

3.2.2. CRITIC + Entropy Weight Method

Referring to the current reasonable practice of linearly combining the weight coefficients calculated by different weighting methods. The CRITIC method and the entropy weight method are applied to comprehensively determine the weight coefficients of each indicator and calculate the corresponding system development index. Where the CRITIC method takes into account the contrast strength and conflict between the indicator data. The entropy weight method emphasizes the dispersion between the indicator, which can make up for the deficiency of the CRITIC method in this aspect. Given this, the CRITIC method and the entropy weight method are used to construct a comprehensive weighting model in this paper, and the specific calculation process is as follows:

Step 1: the following model can be constructed according to the formula of the CRITIC method:

$$c_j = \frac{\sigma_j}{\overline{x}_j} \sum_{l=1}^{m} \left(1 - \left|r_{lj}\right|\right) \tag{1}$$

$$W_j^{(1)} = \frac{c_j}{\sum_{j=1}^{m} c_j} \tag{2}$$

where m represents the total number of indicators. σ_j and $\overline{x}_j$ are the standard deviation and mean values of the standardized indicators of j. r_{lj} is the correlation coefficient of the indicators of l and j. c_j indicates the information quantity of the indicator j. $W_j^{(1)}$ is the CRITIC weight of the indicator of j.

Step 2: Calculate the weights based on the entropy weight method. Since the ordinary entropy weight method has limitations in the longitudinal comparison in time, the time dimension is introduced with the following formula:

$$D_{tij} = x_{tij} / \sum_{t=1}^{q} \sum_{i=1}^{n} x_{tij} \tag{3}$$

$$e_j = -\frac{1}{\ln qn} * \sum_{t=1}^{q} \sum_{i=1}^{n} D_{tij} \ln D_{tij} \tag{4}$$

$$W_j^{(2)} = 1 - e_j / \sum_{j=1}^{m} 1 - e_j \tag{5}$$

where q indicates the length in years. n indicates the number of cities. D_{tij} is the indicator proportion of the j indicator of city i for year t. x_{tij} is the standardized indicator data. e_j is the entropy value of the j indicator. $W_j^{(2)}$ is the weight of the j indicator, which is calculated by the entropy weight method.

Step 3: Combine the weights and calculate the subsystem composite development index as follows:

$$W_j = \alpha W_j^{(1)} + (1 - \alpha) W_j^{(2)} \tag{6}$$

$$S_{ti} = \sum_{j=1}^{m} (W_j * x_{tij}) \tag{7}$$

where W_j is the composite weight of the j indicator; this paper considers that the two weighting methods have the same importance, so $\alpha = 0.5$. S_{ti} is the composite development index of city i for year t.

3.2.3. Modified Coupled Coordination Model

The concept of coupling first came from electromagnetism, used to indicate the physical phenomenon that different electromagnetic waves affect each other and tend to be synergistic. Later the meaning was extended and widely used in economic, social, urban, industrial, and other fields. Currently, the coupled coordination model has become an effective research tool for evaluating the balanced development of social, economic, ecological, and industrial systems. In terms of urban development evaluation, the coupled coordination model can objectively represent the interrelationships and synergistic trends among different systems within a city. Based on this, the coupled coordination model is developed to analyze the multiple coupling relationships and the coordination level among DE, NU, and LE in the Yangtze River Delta, where the coupling degree is a measure of the association degree among subsystems, reflecting the strength of the interaction degree. The effect is not divided into pros and cons. Coordination refers to the benign interaction relationship among subsystems. Therefore, the coordination degree can measure the degree of mutual synergy among subsystems and reflect the process of the overall system from disorder to order. However, the traditional coupling coordination model has problems such as over-reliance on the development of the system itself, weak validity of model use, and uneven distribution of coupling degree. Therefore, referencing the existing related studies [65], this paper further constructs a modified ternary coupling coordination model as follows:

$$C = \sqrt{\left[1 - \frac{\sqrt{(U_3 - U_2)^2 + (U_3 - U_1)^2 + (U_2 - U_1)^2}}{3}\right] * \sqrt{\frac{U_2 U_1}{U_3^2}}} \quad (8)$$

$$T = \delta_1 U_1 + \delta_2 U_2 + \delta_3 U_3,\ \delta_1 + \delta_2 + \delta_3 = 1 \quad (9)$$

$$D = \sqrt{C * T} \quad (10)$$

where C is the coupling degree among the subsystems and values range from [0, 1]. From its formula, it can be seen that the closer the development indexes of the subsystems, the greater the coupling degree. It indicates the stronger association among the subsystems. U represents the DE, NU, and LE systems, both values range from [0, 1], where U_3 is the maximum value among the subsystems. T is the comprehensive development index of the subsystems. δ is the undetermined coefficient for each system, and this paper takes its value as 1/3 because of the consistent importance of the subsystems. D is the coupling coordination degree of the subsystems and the values range from [0, 1], the closer the value is to 1, the higher the level of coordinated development of the subsystems. According to the magnitude of the coupling coordination degree of the subsystems and the research needs, the coupling coordination type of each city in the Yangtze River Delta is divided into three types and refined into five stages, as shown in Table 2.

Table 2. Type division of coupling coordinated development.

Development Type	Coupling Coordination Degree	Coupling Coordination Stage
Coordinated development	$0.7 < D \leq 1$	Good coordination
	$0.6 < D \leq 0.7$	Intermediate coordination
Transformation development	$0.5 < D \leq 0.6$	Basic coordination
	$0.4 < D \leq 0.5$	Basic imbalance
Imbalance development	$0.3 < D \leq 0.4$	Intermediate imbalance
	$0 < D \leq 0.3$	Serious imbalance.

3.2.4. Kernel Density Estimation

In socio-economic studies, kernel density estimation is often used to describe the distribution pattern of economic events and the evolution process of the data. Therefore, the overall distribution and evolutionary trajectory of the coupling coordination of the subsystems are described by the kernel density estimation method in the nonparametric estimation method. When the data obey the same distribution, the formula is as follows:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{a_i - \overline{a}}{h}\right) \quad (11)$$

where n is the number of observed objects. h is the density estimation bandwidth. a_i and $\overline{a}$ are the correlation index and its mean value, respectively. k is the stochastic kernel function, and here a Gaussian kernel function is used.

3.2.5. PVAR Model

There are complex relationships among DE, NU, and LE that are intertwined and influence each other. Thus, there may be endogeneity problems in using ordinary models to identify their coupling mechanism. Based on this, the establishment of a PVAR model can better overcome these problems and also identify the interaction of the subsystems, the specific form is as follows:

$$Y_{it} = \beta_0 + \sum_{f=1}^{p} \beta_f Y_{i,t-f} + \mu_i + \nu_t + \varepsilon_{it} \tag{12}$$

where Y_{it} is the matrix of explained variables in this model, including the log values of DE, NU, and LE. $\sum_{f=1}^{p} \beta_f$ is the matrix of estimated coefficients. β_0 is the constant term. p is the lagged order. μ_i reflects city-fixed effects. ν_t reflects year-fixed effects. ε_{it} is the random error term.

3.2.6. Spatial Panel Model

Cities, as typical spatial units, are bound to have some degree of spatial association, and the spatial econometric model is an effective tool to study the spatial effects. Based on this, through the test of spatial correlation and the comparison of different spatial econometric models, according to the study purpose and theoretical analysis, this paper sets up a spatial Durbin panel model of the following form:

$$D_{it} = \eta_0 + \rho W * D_{it} + \sum_{d=1}^{3} \eta_d U_{dit} + W * \sum_{d=1}^{3} \gamma_d U_{dit} + \phi Z_{it} + \theta W * Z_{it} + \nu_i + \mu_t + \varepsilon_{\text{it}} \tag{13}$$

where D_{it} denotes the coupling coordination degree. U denotes the DE, NU, and LE. Z_{it} is the control variables. W denotes the spatial weight matrix normalized by rows. ρ denotes the spatial autoregressive coefficient, which is used to measure the influence of coupling coordination degree of neighboring cities on local cities. γ_d is the spatial lagged terms of the DE, NU, and LE, which is used to measure the neighbor effects of the subsystems. θ is the spatial lagged terms of the control variables. The rest of the variables are consistent with the above.

4. Empirical Analysis

4.1. Time Evolution Analysis of the Overall Coupling Coordination Development of the Yangtze River Delta

Based on the modified coupling coordination model, the development indexes and coupling coordination degree of the DE, NU, and LE in the Yangtze River Delta are measured for each year from 2011 to 2020. The results are shown in Table 3 and Figure 2.

Table 3. Development indexes and coupling coordination degree of DE–NU–LE in the Yangtze River Delta.

Year	DE	NU	LE	Coupling Coordination Degree	Coupling Degree	Coupling Coordination Stage
2011	0.0943	0.3082	0.4152	0.3811	0.5350	Intermediate imbalance
2012	0.1213	0.3315	0.4290	0.4120	0.5802	Basic imbalance
2013	0.1514	0.3180	0.4271	0.4303	0.6222	Basic imbalance
2014	0.1647	0.3207	0.4359	0.4388	0.6298	Basic imbalance
2015	0.1799	0.3359	0.4446	0.4545	0.6487	Basic imbalance
2016	0.2037	0.3567	0.4498	0.4776	0.6814	Basic imbalance
2017	0.2345	0.3683	0.4463	0.5000	0.7193	Basic coordination
2018	0.2546	0.3837	0.4543	0.5159	0.7360	Basic coordination
2019	0.2690	0.3981	0.4689	0.5278	0.7418	Basic coordination
2020	0.2811	0.4011	0.4724	0.5353	0.7510	Basic coordination

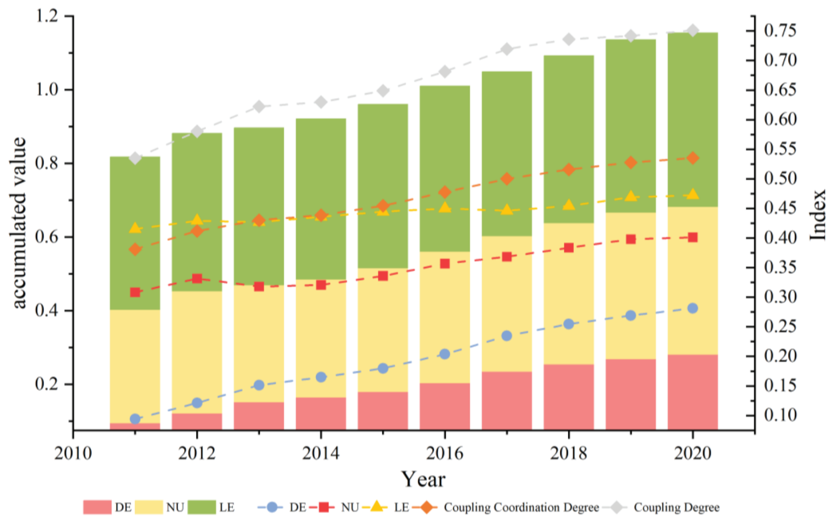

Figure 2. DE–NU–LE coordinated development trends in the Yangtze River Delta.

According to Table 3 and Figure 2, in the Yangtze River Delta, the overall coupled and coordinated developments of the DE, NU, and LE show a stable upward trend from 2011 to 2020. The coupling degree is always higher than the coupling coordination degree and subsystems development indexes. The coupling value increases from 0.54 in 2011 to 0.71 in 2020. The result indicates that the interaction among the subsystems of DE, NU, and LE in the past 10 years has been continuously deepened, and tends towards positive development. The coupling coordination degree increases from 0.38 in 2011 to 0.54 in 2020, which achieves the transition development from moderate disorders to basic coordination as a whole. In terms of the development of subsystems, the development level of DE, NU, and LE are significantly different from 2011 to 2020 but has a gradually converging trend over time. Among them, the LE system shows a slow and fluctuating growth with a brief decline in 2013 and 2017. It has always been in the leading position and has become an important supporting part of the ecological environment of the Yangtze River Delta. The developments of NU and DE show a steady upward trend in general. It is worth noting that NU shows a short decline and stagnation from 2012 to 2014, and then shows a more moderate growth trend. The reason may be that the Yangtze River Delta region, as a highland of policy innovation and reform, had already started relevant constructions before the official launch of NU in 2014. After a short throe of deep reforms, it has gradually promoted the urbanization transition from traditional to new-type. The high-quality development of multi-dimension has become the goal of each city. Similarly, after three years of rapid growth, the growth rate of DE slowed down after 2013. Under the joint action of fluctuation growth of the LE, urbanization reforms, and the slowdown of the DE development, the growth of the coupling coordination degree has also experienced a process of "slowing down-accelerating-slowing down again" after 2012.

4.2. Spatial and Temporal Evolution Characteristics of DE–NU–LE and Coupling Coordination Degree in the Yangtze River Delta Prefecture-Level Cities

4.2.1. The Foundations for Coordinated Development of Each City Have Begun to Form, and the Trend of DE Polarization Is Obvious

Based on the indicators in Table 1 above, the development indexes of DE–NU–LE of each prefecture-level city in the Yangtze River Delta are calculated by the CRITIC + entropy weight method. Figure 3 demonstrates the changes of DE–NU–LE and the coupling coordination degree over different years.

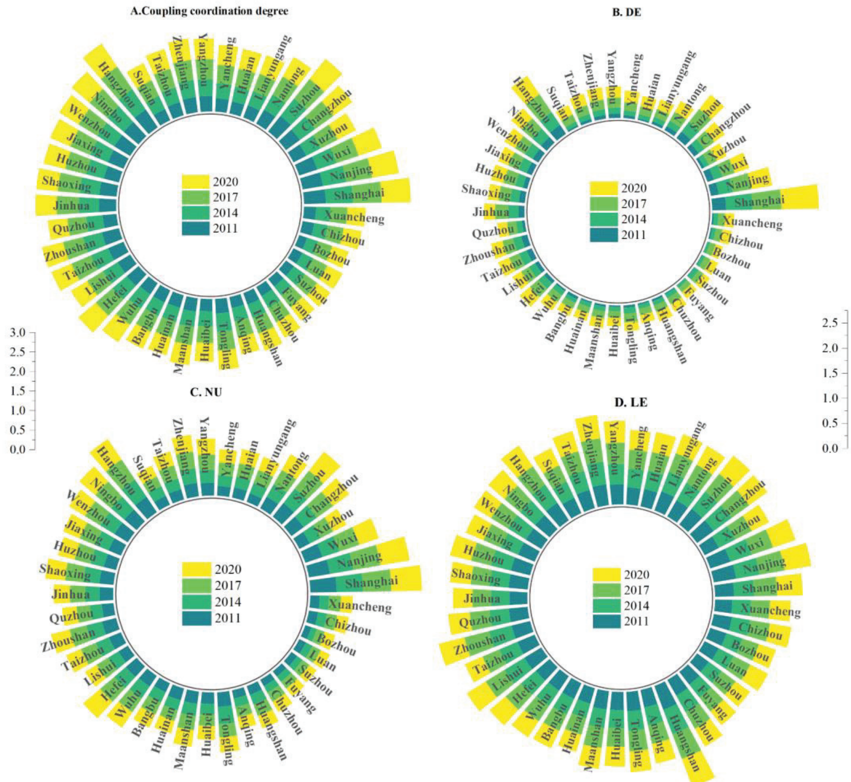

Figure 3. The changes of DE–NU–LE and the coupling coordination degree of each prefecture-level city in the Yangtze River Delta over different years. ((**A**) presents the change of the coupling coordination degree. (**B**) presents the change of DE. (**C**) presents the change of NU. (**D**) presents the change of LE).

Figure 3A represents the changes over different years in the coupling coordination degree of each prefecture-level city in the Yangtze River Delta. It can be seen that the coupling coordination degree of each city has developed significantly in each period, showing a clear gradient pattern with a distinct circle structure. Shanghai and Hangzhou are at the first level. In particular, Shanghai, as the only municipality directly under the central government in the Yangtze River Delta, has always been in the leading position regarding coupling coordination degree. Nanjing, Wuxi, Suzhou, and Ningbo are at the second level with good geographical locations and development foundations. The rest of the cities are located at the third level, with a relatively low coupling coordination degree. It is worth noting that from 2014 to 2017, the coupling coordination degree of the cities had the most significant increase, with the overall average level rising from 0.44 to 0.50. During this period, the connotation of NU is greatly enriched, and the ecological civilization construction and the idea of sustainable development gradually gained popularity. Meanwhile, with the arrival of the mobile digital era, the related digital constructions such as digital city and smart city continuously strengthen the coupling state among DE, NU, and LE. Further, the benign interaction can be promoted to complete the stage transformation of the overall coordinated development from imbalance to coordinated.

In terms of the changes of the subsystems, the development of DE shows a pattern with the three pillars of Shanghai, Nanjing, and Hangzhou. The low value is in Anhui Province, which is basically lower than the regional average (Figure 3B). The development of the DE requires sustained talent investment and technological breakthroughs. Shanghai, Hangzhou, and Nanjing not only have strong economic strength, but also have abundant talent reserves and complete basic information facilities. As regional central cities, they have certain advantages in resource utilization efficiency and policy tendency. From the perspective of local administrators, the leading DE development of Shanghai, Hangzhou, and Nanjing cannot be achieved without the attention of local governments. By combing through the local plans of DE development, it is easy to find that Hangzhou and Shanghai managers are more focused on enhancing the development drivers of the DE and the expansion of related application fields. They are committed to establishing themselves as the leading highland of DE development by breakthroughs in new technologies and new fields. Nanjing is more focused on the integration of the DE with production, life, and ecology, to enhance its universality and inclusion. While Anhui Province is dominated by agriculture and traditional industries, with a weak foundation for digital development, the digital industry has not yet formed a scale. Hence, the digital gap with other cities is becoming increasingly obvious. The NU shows a relatively balanced development (Figure 3C). Among them, Shanghai, Nanjing, Suzhou, Hangzhou, and Hefei have great guiding functions, but the NU level of some cities in Anhui Province and north of Jiangsu Province still needs to be improved. The circle shape of LE is relatively plump and presents an overall balanced development during the study period (Figure 3D). The result points out that all cities in the Yangtze River Delta have a good foundation of LE. The periodic increase is small, indicating that the improvement of LE has a certain pressure. The superior land foundation benefits from the natural geographical advantages of the Yangtze River Delta. First of all, the Yangtze River Delta has good agricultural foundations with a dense river network and fertile soil. Secondly, the inland cities are mainly hilly areas with stable geological conditions, abundant water sources, and low incidence of natural disasters. Correspondingly, the solid land environment also means that the improvement of LE is not easy.

4.2.2. The Spatial Evolution Characteristics of Subsystems Are Different, and the Spatial Pattern of "High in the East and Low in the West" Is Gradually Strengthened

Columns A, B, and C of Figure 4 show the spatial distribution characteristics of DE, NU, and LE in the Yangtze River Delta from 2011 to 2020, respectively. First of all, from the spatial evolution characteristics of DE, Shanghai has the highest score of 0.33 in 2011, followed by Hangzhou at 0.25. The overall DE development level is low, and most of the cities are in "digital winter", especially in the northern part of Jiangsu Province and the whole area of Anhui Province, which shows the characteristics of low-level clustering of DE. In 2014, DE development shows a trend of gradually spreading outward with Shanghai, Hangzhou, and Nanjing as the center. In 2020, Shanghai, Hangzhou, and Nanjing had become important advantageous cities for DE development in the Yangtze River Delta, and the development gap with surrounding cities continues to widen. It is visible that in the Yangtze River Delta, the DE is still in the early stage of development and requires a large amount of resource investment. Shanghai, Nanjing, and Hangzhou have gradually become the digital growth poles by their scale advantages and digital foundation. In general, the development of the DE in the Yangtze River Delta is significantly polarized, and the overall development level still has a lot of room for improvement.

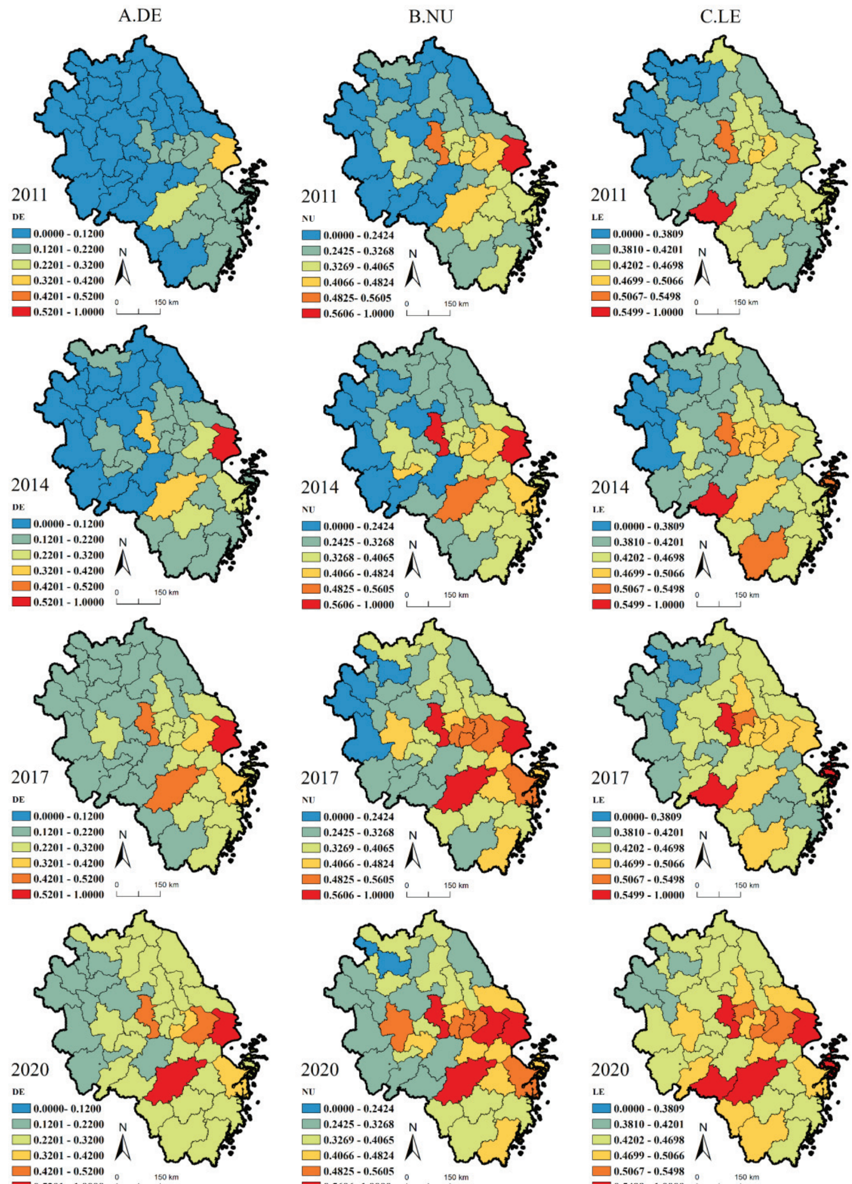

Figure 4. Spatial evolution characteristics of DE–NU–LE. ((**A**) presents the four-year changes of DE. (**B**) presents the four-year changes of NU. (**C**) presents the four-year changes of LE).

Secondly, from the spatial evolution characteristics of NU, Shanghai still achieved the highest score at 0.64 in 2011, followed by Nanjing and Hangzhou at 0.52 and 0.46, respectively. Some low values still clustered in the northern and western part of the Yangtze River Delta. Compared with the polarized advantage of DE in individual cities, NU shows a more balanced development. The Z-shaped distribution with metropolitan areas of Shanghai, Nanjing, Hefei, Hangzhou, and Ningbo as the main axis has gradually formed in 2014 to 2020. The Z-shaped pattern of NU is highly consistent with the pattern of population distribution and economic development in the Yangtze River Delta. This phenomenon indicates that population and economy are the basis for the sustainable promotion of NU. The NU with the people-oriented concept cannot be separated from individual labor and development, and the economic foundation is the basic guarantee for the continuous deepening of NU. On the whole, the overall development of NU in the Yangtze River Delta shows a positive trend from 2011 to 2020, and the gap between cities has gradually narrowed. The spatial distribution presents an obvious Z-shaped pattern, and continuously deepens into the central, southern, and northern regions.

Finally, LE exhibits a very different spatial distribution from that of the DE and NU. Huangshan has the highest score of 0.57 in 2011, followed by Nanjing and Wuxi at 0.51 and 0.47, respectively. Most cities obtain scores between 0.3 and 0.45 with small differences between cities, and a small number of low values gather in the northwest of the Yangtze River Delta. In 2014–2020, the spatial distribution pattern with "Chizhou-Lishui" and "Nanjing-Zhoushan" as two horizontal lines, and "Quzhou-Nantong" as one vertical line has gradually formed. Compared with the spatial distribution patterns of DE and NU, the spatial evolution path of LE shows obvious ecological characteristics. Although the economic development and urbanization construction of Huangshan, Quzhou, Lishui, Chizhou, and Zhoushan are relatively backward. They still have significant ecological advantages and green development potential with abundant natural resources, high vegetation coverage, and stable ecological environment, forming an important ecological protective screen in the Yangtze River Delta. Besides, in these cities, local governments strongly support eco-industries such as tourism, wellness, and culture to promote them as a new green driving force for local development. Nanjing, Suzhou, Shanghai, Hangzhou, and Wuxi not only take the lead in economic development and urban construction, but also have good performance in LE. This shows that the good development of LE not only comes from the natural advantages, but also the active practice of the ecological concept by governments, which feeds the achievements of economic development back into the ecological construction. Generally, the development of LE in the Yangtze River Delta tends to be balanced from 2011 to 2020, and the development pattern of two horizontal lines and one vertical line has emerged.

The spatial distribution characteristics of the coupling coordination degree of the subsystems in the Yangtze River Delta from 2011 to 2020 are shown in Figure 5. In terms of the coupling coordination degree, the spatial distribution of coupling coordination is dominated by low-level and non-uniform distribution in the early stage. The reason may be that the early DE and NU are at a low-level of development, and it is difficult to form a good interactive relationship with LE. In the middle and late period of the study, the development gap among DE, NU, and LE gradually narrowed, and even overtook in some cities. The coupling degree of the subsystems is increasing, the coupling coordination degree is distributed in sheets. The pattern of "high in the east and low in the west" is more and more significant.

From the perspective of the spatial evolution path, Shanghai, Hangzhou, Nanjing, and Suzhou, only four cities, are in the basic coordination stage in 2011, while the rest are in the imbalance stage; and where Anqing, Chuzhou, Lu'an, Suzhou, Fuyang, and Bozhou are in the serious imbalance stage. At this time, only Shanghai and Nanjing have advanced development of NU, while the rest of the cities have certain advantages in LE. In 2014, Shanghai, Hangzhou, and Nanjing entered the intermediate coordination stage. Wuxi, Ningbo, Jinhua, and Wenzhou moved from the basic imbalance stage to the basic coordination stage, and Bozhou is still in the serious imbalance stage. Hangzhou changed from the advanced development of LE to the advanced development of NU. In 2017, Shanghai took the lead in entering the good coordination stage, and Suzhou moved from the basic coordination stage to the intermediate coordination stage. With the approval of the Yangtze River Delta urban agglomeration in 2016, the integrated development of the Yangtze River Delta has become a national proposition, and the connection of cities has been further strengthened. However, only partial cities in Anhui Province have joined the Yangtze River Delta urban agglomeration. Thus, the map shows that the large number of yellow patches deepen to the southern region, and green patches spread to the northern region. Meanwhile, Nanjing, Wuxi, Suzhou, Shanghai, Jiaxing, Hangzhou, Shaoxing, Ningbo, and Hefei have advanced development of NU, which indicates that NU has certain development advantages in regional central and sub-central cities. The leading cities of NU are mainly distributed on the Z-shaped axis, which is consistent with the evolution characteristics of NU above. *The outline of the integrated regional development of the Yangtze River Delta* in 2019 includes the whole region of Anhui Province in the development plan of the Yangtze River Delta. The coordinated development of the Yangtze River Delta is pushed towards a new stage. Therefore, in 2020, more than half of cities in the Yangtze River Delta enter the coordination stage, and Hangzhou shifts from the intermediate coordination stage to the good coordination stage. The yellow patches begin to cover the green patches from east to west and south to north. Hefei, Wuhu, and Maanshan, which are close to Nanjing and Hangzhou, have taken the lead in developing well in Anhui Province due to the effect of proximity. The rest of the cities in Anhui Province are still relatively backward in coordinated development because of the weak development foundation, even though they are radiated by central cities. The gradation pattern of "high in the east and low in the west" becomes clearer. At this time, Shanghai has greatly advanced development of DE, and the development advantage of NU is still concentrated in some central cities that are on the Z-shape axis. The remaining cities are still dominated by the advantages of LE. The advance of LE and the relative lag of DE and NU in most cities may cause changes in the internal functions and structures of the city system. The coordinated development of the subsystems may be restricted to a certain extent.

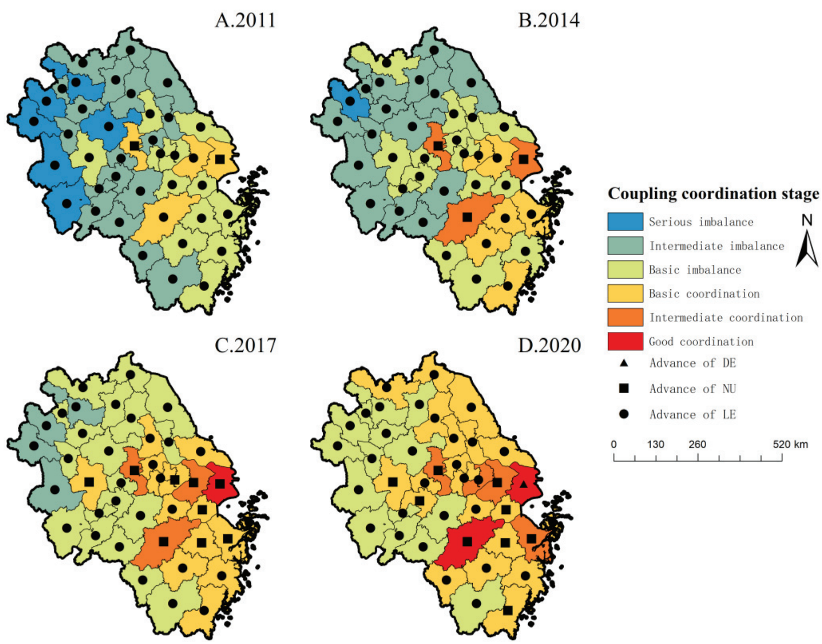

Figure 5. Spatial evolution characteristics of the coupling coordination degree. ((**A**) presents the change of the coupling coordination degree in 2011. (**B**) presents the change of the coupling coordination degree in 2014. (**C**) presents the change of the coupling coordination degree in 2017. (**D**) presents the change of the coupling coordination degree in 2020).

4.2.3. The Tailing of the Right Side Is Apparent, and Regional Development Gradually Converges

From the above analysis, it can be seen that the overall coordinated development of DE, NU, and LE in the Yangtze River Delta has stably improved, and each city initially has the foundation of coordinated development, while the evolutionary trajectory of the subsystems varies and development differences still exist. Therefore, kernel density estimation is further used to reveal the dynamic evolution characteristics of the coupling coordination degree and the subsystems (Figure 6).

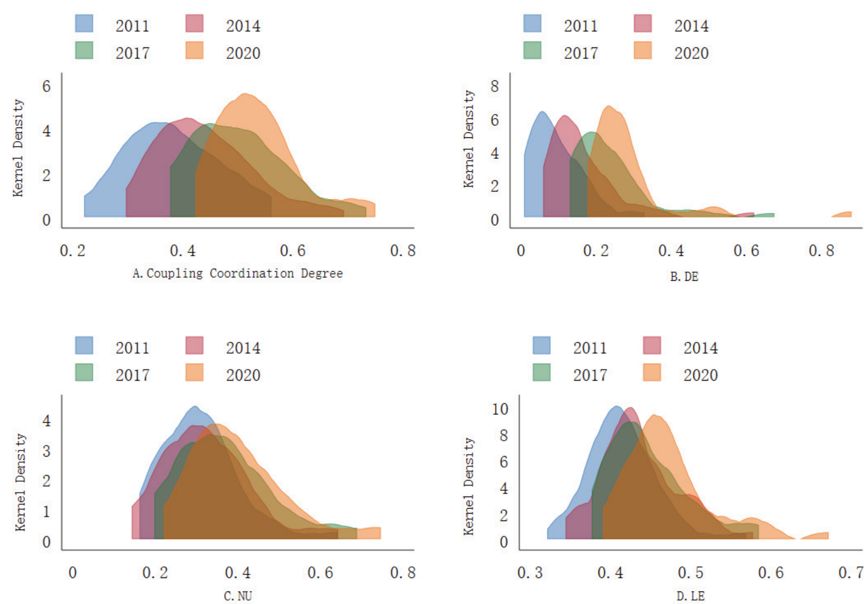

Figure 6. Kernel density analysis of the coupling coordination degree and the subsystems. ((**A**) represents the kernel density change of coupling coordination degree. (**B**) represents the kernel density change of DE. (**C**) represents the kernel density change of NU. (**D**) represents the kernel density change of LE).

From the position covered, the overall kernel density curve of coupling coordination degree gradually shifts to the right. This moving trend indicates that the overall coordinated development level of the subsystems in the Yangtze River Delta is gradually improving. In 2011–2014 and 2014–2017, the span of the curve shifting to the right is more obvious than other periods, which indicates that the growth rate of coordinated development level has accelerated during this period. From the shape of the curve, the kernel density curve shows a more obvious trailing feature to the right from 2014 to 2020. The wave width tends to contract and the wave peak gradually becomes larger. These characteristics indicate that the gap between the coordinated development levels of the Yangtze River Delta cities are gradually decreasing. However, the phenomenon of individual cities that have unique development advantages such as Shanghai still exist. In terms of the evolution of the subsystems, the kernel density curve of DE shows an obvious trend of moving to the right, with an overall slender shape, and the trailing feature to the right intensifies over time. All of these characteristics suggest two phenomena. One is that the development gap among the cities in the Yangtze River Delta tends to narrow. The other is that individual cities such as Shanghai, Nanjing, and Hangzhou show certain accumulative advantages and are far ahead in the development of DE. The kernel density curves of NU and LE both show a similar overlapping trend during the study period, which indicates a slower pace of development for NU and LE. Additionally, both the tailings of the right side tend to become thicker and longer, especially LE, with a trend of change from unipolar to multipolar development, indicating that the development of LE is reflected at all levels, and the overall structure tends to be stable.

5. Identification of the Interaction Mechanisms and Spatial Effects of DE, NU, and LE

5.1. Interactive Response Identification of DE, NU, and LE

To further explore the dynamic interaction effects of the DE, NU, and LE, this paper employs the PVAR model to quantitatively analyze the dynamic relationships among the subsystems. To avoid the pseudo-regression problem caused by the root unit, the original data are logarithmically processed to make them stationary. The results of LLC and IPS tests are shown in Table 4.

Table 4. Data stationarity test.

Variance	LLC	IPS	Individual Fixed	Time Trend	Test Results
ln_DE	−34.5572 ***	−11.4447 ***	Yes	Yes	Stationary
ln_NU	−8.8700 ***	−3.3008 ***	Yes	Yes	Stationary
ln_LE	−16.5960 ***	−5.2458 ***	Yes	Yes	Stationary

* Note: *** indicate significance at the 1% statistical levels.

The Grange causality test in Table 5 indicates that there is a two-way causal relationship between DE, NU, and LE. The optimal lag period is determined to be two according to the AIC criterion, so the PVAR (2) model is established. Based on this, the impulse response analysis of DE, NU, and LE is carried out with Stata to explore the dynamic interaction and response trends among the subsystems. The results are shown in Figure 7.

Table 5. Granger causality test.

Equation	Excluded	*p*-Value	Whether to Reject the Null Hypothesis
ln_DE	ln_NU	0.002 ***	Rejection
	ln_LE	0.048 **	Rejection
	All	0.000 ***	Rejection
ln_NU	ln_DE	0.000 ***	Rejection
	ln_LE	0.060 *	Rejection
	All	0.000 ***	Rejection
ln_LE	ln_DE	0.018 **	Rejection
	ln_NU	0.005 ***	Rejection
	All	0.001 ***	Rejection

* Note: *, **, and *** indicate significance at the 10%, 5%, and 1% statistical levels, respectively. The null hypothesis: B is not the Granger cause of A.

The following results can be found in Figure 7: (I) The responses of DE, NE, and LE to their own standard deviation information shocks in the Yangtze River Delta show a significant positive response (Figure 7A,E,I). The responses are the largest at the beginning of the period and then begin to weaken until it tends to be stable. This trend indicates that the development of each subsystem in the Yangtze River Delta has positive progressive effects and inertial development characteristics. Where the self-reinforcing effect of DE is the most persistent until the 10th period. The self-reinforcing effect of NU is relatively short-lived until the 5th period. The self-reinforcing effect of LE continues until the 9th period. The above descriptions indicate that the development of each subsystem in the Yangtze River Delta shows different degrees of self-reinforcing effects and path-dependent characteristics, and both weaken over time. (II) When facing the shock of NU, DE shows a significant positive response at the beginning of the period (Figure 7B) and reaches a peak in period 1. Then it starts to decline and turn into a negative response and tends to stabilize from period 4, with insignificant response. Similarly, DE does not respond significantly to the shock of LE (Figure 7C). With the further deepening of NU and the extension of ecological concepts, the digital technology and its application have received unprecedented attention. However, the current urbanization quality and ecological civilization construction still need to be improved, which means that the stimulation for the development of DE is limited. Especially, the support for related technology is weak and has not yet formed a breakthrough power to promote it. (III) NU shows a significant positive response in general when facing the shock of DE. It peaks in period 3 after a short period of ups and downs, and then starts to fall back and stabilizes after period 14 (Figure 7D). This indicates that DE shows sustaining growth momentum and development potential in the process of integration with NU, which improves the level of urban digitization. For the shock of LE, NU shows a non-significant negative response (Figure 7F). Although LE plays a supportive role for NU, the land contradiction between urban development and land conservation has been long-standing, especially in the early crude city development mode, which has problems such as weak ecological awareness and over-exploitation of land. It is difficult to support the NU through the function of resource guarantee and wealth appreciation. (IV) LE shows a significant positive response in general when faced with the shock of DE (Figure 7G). The initial response is the strongest, then weakens in a fluctuating manner and tends to be stable. This indicates that with the DE development, the application of digital technology related to digital planning, intelligent land monitoring, and digital governance has effectively improved the city's ability to protect LE. For the shock of NU, LE shows a significant positive response at the beginning of the period and becomes negative and insignificant in period 1, and then rebounds rapidly (Figure 7H). This result indicates that the NU, which is oriented towards greenness and intensification, plays a certain guiding role in the protection of LE. However, the symbiosis between development and conservation still restricts the coordinated development of both, and even creates a stress effect between the two.

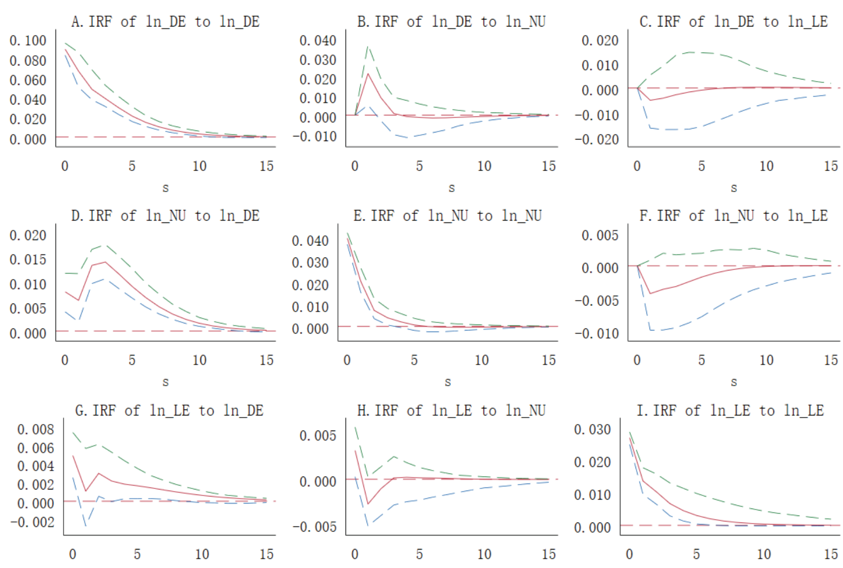

Figure 7. The impulse response analysis of DE, NU, and LE. ((**A**) represents the impulse response of ln_DE to ln_DE. (**B**) represents the impulse response of ln_DE to ln_NU. (**C**) represents the impulse response of ln_DE to ln_LE. (**D**) represents the impulse response of ln_NU to ln_DE. (**E**) represents the impulse response of ln_NU to ln_NU. (**F**) represents the impulse response of ln_NU to ln_LE. (**G**) represents the impulse response of ln_LE to ln_DE. (**H**) represents the impulse response of ln_LE to ln_NU. (**I**) represents the impulse response of ln_LE to ln_LE).

5.2. Spatial Effects Identification of DE–NU–LE Coordinated Development

The spatial and temporal differentiation characteristics and dynamic interaction mechanism of the DE, NU, and LE in the Yangtze River Delta from 2011 to 2020 are analyzed above. In order to further identify the spatial effects of the subsystems and the coupling coordination degree, a spatial panel model is established according to formula (13) based on verifying the spatial positive correlation of the coupling coordination degrees. Table 6 reports the test results of the spatial correlation of the coupling coordination degree in the Yangtze River Delta.

Table 6. Data stationarity test.

Year	Adjacency Matrix			Economic Distance Matrix		
	Moran's I	Z-Value	*p*-Value	Moran's I	Z-Value	*p*-Value
2011	0.449	4.812	0.00	0.186	9.635	0.00
2012	0.460	4.918	0.00	0.187	9.665	0.00
2013	0.394	4.283	0.00	0.161	8.536	0.00
2014	0.394	4.314	0.00	0.154	8.268	0.00
2015	0.400	4.362	0.00	0.161	8.574	0.00
2016	0.386	4.211	0.00	0.157	8.376	0.00
2017	0.416	4.512	0.00	0.167	8.832	0.00
2018	0.400	4.512	0.00	0.162	8.605	0.00
2019	0.360	3.955	0.00	0.162	8.042	0.00
2020	0.318	3.548	0.00	0.130	7.200	0.00

From the results in Table 6, it can be found that the global Moran's I index values are all greater than 0 and significant at the 1% statistical level. It indicates that the spatial distribution of the coupling coordination degree in the Yangtze River Delta has a significant positive correlation. The prerequisite assumption of the spatial econometric model is satisfied. The global Moran's I index calculated by the different spatial weight matrices shows a fluctuating general downward trend during the study period. For the numerical value, the value of the global Moran's I index reaches its maximum value in 2012, when the spatial agglomeration of the coupling coordination degree is strongest. Additionally, it then begins to decline in a fluctuating manner. The index value in 2020 is smaller than its initial value, indicating that the spatial non-balanced development of the coupling coordination degree in the Yangtze River Delta has been improved after the continuous adjustment from agglomeration to dispersion.

In order to precisely identify their spatial effects and avoid estimation bias caused by omitted variables, the following variables are controlled: (I) The level of government income, measured by the proportion of government fiscal revenue in the GDP. (II) The level of government expenditure, measured by the proportion of government fiscal expenditure in the GDP. (III) The level of foreign investment, measured by the proportion of actually utilized foreign investment in the GDP. (IV) Consumption demand, measured by the proportion of retail sales of consumer goods in the GDP. Based on the above variables, a spatial panel model is constructed and the tests of corresponding spatial econometric model selection are conducted. The results in Table 7 show that both the LR test and the Wald test significantly reject the hypothesis that the spatial Durbin model (SDM) degenerates into the spatial autoregressive model (SAR) or the spatial error model (SEM) at the 1% statistical level. The Hausman test indicates that a fixed-effects model should be used.

Table 7. Selection of spatial econometric models.

	SDM→SAR		SDM→SEM
LR-test	59.23 ***		42.47 ***
Wald-test	64.56 ***		41.18 ***
Hausman		39.46 ***	

* Note: *** indicate significance at the 1% statistical levels.

Table 8 reports the estimation results of the SDM based on different spatial weight matrices. The results show that regardless of which spatial weight matrix is used, the coefficients of DE and NU are significantly positive at the 1% statistical level. While the coefficient of LE is significantly negative at the 1% statistical level. Those results empirically prove the above conjecture that the development of DE and NU lags behind relative to LE in the Yangtze River Delta. This has to some extent caused uneven development among subsystems, which has a constraining effect on the overall coordinated development. The coefficient of ρ, which is the spatial lag term of the coupling coordination degree, is significantly positive. Indicating that the coordinated development degree of the subsystems has a significant spatial spillover effect, which can promote the coordinated development level of neighboring cities.

Table 8. Estimation results of the spatial Durbin model.

Variance	(1) Adjacency Matrix ln_D	(1) Adjacency Matrix Wx	(2) Economic Distance Matrix ln_D	(2) Economic Distance Matrix Wx
ln_DE	0.1872 ***	−0.0680 ***	0.1873 ***	−0.0512 ***
	(0.0038)	(0.0126)	(0.0038)	(0.0088)
ln_NU	0.2818 ***	−0.0250	0.2868 ***	−0.0335 **
	(0.0105)	(0.0291)	(0.0103)	(0.0164)
ln_LE	−0.0611 ***	0.0857 **	−0.0478 ***	0.0557 ***
	(0.0174)	(0.0344)	(0.0171)	(0.0215)
Control variables	Yes		Yes	
ρ	0.2624 *** (0.0660)		0.2041 *** (0.0440)	
N	410		410	
R2	0.989		0.988	

* Note: Robust standard errors based on city level are in parentheses. **, and *** indicate significance at the 5%, and 1% statistical levels, respectively. The following table is the same.

Since the regression coefficient of the spatial lag term is significantly not 0, simply using the regression coefficient to measure the spatial effect of each subsystem will have systematic bias. Hence, it is necessary to decompose the effect to obtain the direct and indirect effects of each subsystem, and the results are shown in Table 9.

Table 9. Decomposition of spatial effects.

Variance	(1) Adjacency Matrix ln_D		(2) Economic Distance Matrix ln_D	
	Direct effect	Indirect effects	Direct effect	Indirect effects
ln_DE	0.1862 ***	−0.0249 ***	0.1865 ***	−0.0156 ***
	(0.0038)	(0.0065)	(0.0038)	(0.0037)
ln_NU	0.2844 ***	0.0653 **	0.2882 ***	0.0305 **
	(0.0104)	(0.0267)	(0.0102)	(0.0122)
ln_LE	−0.0551 ***	0.0910 **	−0.0427 ***	0.0552 **
	(0.0164)	(0.0428)	(0.0162)	(0.0244)

* Note: **, and *** indicate significance at the 5%, and 1% statistical levels, respectively.

The results in Table 9 show that the direct effects of DE, NU, and LE are consistent with the above analysis results and show better robustness under different spatial weight matrices. This result indicates that the uneven development within the subsystems mainly restricts the coordinated development of local cities. In terms of indirect effects, the coefficient of DE is significantly negative, indicating that the DE development of local cities negatively affects the coordinated development of neighboring cities. This result is in line with the spatial and temporal evolution of DE. The reason behind it may be that the development of DE requires continuous breakthroughs in technology and continuous investment of high-quality talents. As a result, regional diffusion cannot be formed in the short-term. Instead, it will produce a certain “siphon effect” on the resource endowment of neighboring cities, which is manifested in the accumulated advantages of digital development in individual cities such as Shanghai, Hangzhou, and Nanjing in reality. The indirect effects of NU and LE are both significantly positive, indicating that NU and LE have good spatial spillover effects. Particularly for the LE, the absolute value of the indirect effect is greater than the direct effect, which indicates that the improvement of regional coordination level is more dependent on the spatial spillover effect of LE. Additionally, it also reflects the publicity and universality of LE itself. Hence, accelerating the construction of NU and strengthening the protection of LE are not only beneficial to the development of local cities but also effectively promote the coordinated development of the region as a whole.

6. Conclusions and Suggestions

6.1. Main Conclusions

Based on the discussion of the coupling mechanism, the relative analysis described herein is applied to investigate the spatial and temporal characteristics of DE–NU–LE and the coupling coordination degree, with the Yangtze River Delta as the study area. Additionally, the dynamic interactions and spatial effects of LE, NU, and LE are further identified by the econometric model. The main findings are as follows:

First, in terms of the overall development of the Yangtze River Delta, DE, NU, LE, and coupling coordination generally show a stable upward trend. Among the subsystems, the overall development of LE is in the lead, and there is a gradual convergence trend among the subsystems over time. In terms of coupling coordination, the coupling degree is always greater than the coupling coordination degree and the development index of each subsystem, indicating that the connection among the subsystems is increasingly strengthened.

Second, in terms of spatial and temporal evolution, the subsystems and the coupling coordination show different evolutionary characteristics. The DE shows a tripod complexion of Shanghai, Hangzhou, and Nanjing, and the trend of polarization is obvious. The NU is distributed in a Z-shape with metropolitan areas of Hefei, Nanjing, Shanghai, Hangzhou, and Ningbo as the main axes. The LE shows a more balanced development trend during the study period, and gradually forms a spatial pattern of two horizontals of “Chizhou-Lishui” and “Nanjing-Zhoushan” and one vertical of “Quzhou-Nantong”. The coupling coordination shows a typical pattern of “high in the east and low in the west” and has a tendency to spread horizontally from east to west.

Third, DE, NU, and LE in the Yangtze River Delta all have positive progressive effects and path-dependent characteristics, and the influence on themselves weakens over time. Among them, the self-reinforcing effect of DE lasts the longest. The DE has a lasting and strong driving effect on NU and LE, but the demand stimulation of NU and LE for DE still needs to be strengthened. The interaction between NU and LE is basically insignificant, which reflects the inherent land contradiction between urban development and land conservation.

Fourth, there are significant spatial effects of the DE, NU, LE, and the coupled coordination degree in the Yangtze River Delta, where the DE shows an obvious “siphon effect”, which attracts the resource elements of surrounding cities and has adverse effects on their coordinated development. The NU and LE both have significant spatial spillover effects and can promote the coordinated development of neighboring cities.

6.2. Related Suggestions

Based on the above conclusions, this paper puts forward the following suggestions:

First, the administrators of the city should adhere to the concept of sustainable and coordinated development and perfect the integration mechanism of DE, NU, and LE. At present, differences in the development of subsystems still exist. Therefore, the administrators must fully understand the development characteristics of each subsystem and always carry out the concept of sustainable development. The old route of construction at the expense of the ecological environment should be discarded. The holistic view and the inner coupling mechanism of the subsystems should be established and clarified; thus, coordinating the implementation from the perspective of the whole area together with building to closely integrate the development of the DE, NU, and LE with the high-quality development of the Yangtze River Delta.

Second, each city should actively explore differentiated development paths and accelerate the integration of digital technology with economic and social development. First of all, Shanghai, Hangzhou, and Nanjing should increase investment in the development of the digital economy and speed up the promotion of the digital economy from polarization to diffusion. At the same time, local outstanding high-tech enterprises and Internet enterprises should play a positive role in achievement of transformation. The digital advantages of big cities can be converted into digital power for regional common development through knowledge diffusion and result sharing. Secondly, for the cities in Anhui Province with a lower level of coordinated development, on the one hand, they should seize the opportunity of the integrated development of the Yangtze River Delta region. Forming a synergistic development in economy and industry by the enhancement of collaboration and exchange with Jiangsu, Zhejiang, and Shanghai. A green development pattern should be built through the common protection, common monitoring, and common governance in the ecological field. On the other hand, cities in Anhui Province should focus on strengthening their development foundation; specially to strengthen the construction of northern Anhui to avoid the development gap between the north and the south continuing to expand. The advantages in agriculture, manufacturing, and energy industry should be emphasized. Through the application of digital technology, empowering agricultural production, accelerating the transformation of manufacturing, and improving the efficiency of energy create typical farms and factories for the Yangtze River Delta. Finally, for some ecological cities with a slightly weaker economic base such as Huangshan, Zhoushan, Lishui, and Huzhou, the current ecological and resource advantages are utilized fully to further solidify the ecological base of the Yangtze River Delta. The establishment of green ecological cities can enable ecological welfare to cover more areas and benefit more people through the externality of ecological environment and urban development.

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The Evolution of the Waterfront Utilization and Sustainable Development of the Container Ports in the Yangtze River: A Case Study of the Yangtze River Delta

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Abstract: Waterfront resources are an important support system for the social and economic development within the region along the Yangtze River. Container ports are an important component of the Yangtze River port system, as well as for the growth point of waterfront utilization. Based on the summary of remote sensing images and relevant data, this paper calculates the waterfront utilization of the container ports along the Yangtze River in the Yangtze River Delta (YRD), analyzes the waterfront organization pattern and change characteristics, and puts forward the enlightenment and countermeasures for the sustainable development of the port waterfronts. Extending the study of port resources from coastal areas to inland areas is an academic contribution of this paper. At the same time, it has practical significance for the high-quality development of port and shipping and the development and protection of land resources along the Yangtze River. In the YRD, the waterfront utilization of container ports has increased along the Yangtze River, showing a decrease from downstream to upwards, and it has formed dense zones attached to the central cities and major manufacturing bases. The ports with higher length of waterfront are mostly located in the shipping central cities and the Yangtze River estuary. The development direction of container ports is large-scale and specialized. The utilization of the container port waterfront is approaching the periphery of the city and areas with convenient transportation. The utilization of container port shorelines will be close to the periphery of the city and convenient transportation areas. The container port waterfronts occupy the ecological reserve, and the conflicts are expanding with the development of shipping, mainly distributed in the Yangtze River estuary. Based on the empirical analysis, this paper puts forward four enlightenments. First, the exploitation and utilization of the port waterfront has experienced multiple stages of "exploitation—conflict—mitigation". With the transformation of productive waterfront utilization, the pattern of sustainable development along the Yangtze River has changed. Secondly, the conflict between waterfront utilization and protection is inevitable. Additionally, it is necessary to face up to the temporary rapid rise of encroachment on the reserve. Third, through the horizontal coordination of the port system along the river, the original focus on the hub cities will be transferred to the comprehensive consideration of the port cities in the whole region, and the waterfront load of different types of container ports can be balanced. Fourth, the Yangtze River Delta integration mechanism can solve the barriers between higher and lower levels or between different departments and cities.

Keywords: waterfront utilization; container port; port system; Yangtze River

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1. Introduction

Ports are gateways for countries and regions to access international trade, and more than 90% of goods in transnational transportation are transported by shipping. As the global trading system changes and the vertical integration of production and distribution continues to improve, the form of international trade has shifted from traditional cargo transportation to cross-border flow and allocation of multiple production factors, such as capital, technology, information, and talent. By participating in global production and circulation, the scale and function of the port system have changed, resulting in new freight modes and port divisions [1,2]. Ports are not only transshipment sites for transporting goods between land and water, but they are also important nodes in the global logistics system where a large number of derivative services gather [3,4]. By establishing a unified transportation and service network between countries and regions [5,6], nowadays, the global supply chain based on ports is seen as an undeniable force in changing the world political and economic order [7]. In this process, the widespread use of containers has driven suppliers to use standardized modules for transportation [8,9]. After the 1980s, new container ports have been built, or existing ports have been renovated around the world to enable them to operate containers, gradually forming a multi-level container port system covering all regions of the world [10,11].

As the intersection and overlap between ports and hinterlands intensify, inland waterway transport generates more economic activities, and it stimulates the agglomeration of derivative services through the contact advantage of multiple inland nodes. A new stage of regionalization has emerged in the evolution of the port system [12], with the starting point of container shipping extending from coastal areas to inland areas [13,14]. Coastal and inland transportation networks jointly drive the evolution of port systems [15,16]. As the inland transportation service system becomes complex and the proportion of inland logistics costs in total costs continues to rise [17], the focus of the logistics industry development has shifted to inland regions. In this process, container transportation utilizes its cost advantage of convenient transshipment among various transportation modes to connect different types of ports along the river [18], promoting the economies of scale and economies of scope that integrate coastal areas and inland areas. Inland ports change the regional pattern of single external shipping exports by connecting to container liners and undertaking hinterland cargo flows [19,20], There are multi-level hub ports in the inland areas, which has promoted the rapid growth of container ports along the river.

The Yangtze River is an important part of the "T" layout of China's territorial development [21], making it play an important role in the national transportation pattern. By combining the huge container throughput of seaports, especially Shanghai and Ningbo, with inland waterway corridors, the layout of transshipment hubs along the river expands to the hinterland range and achieves logistic accessibility [22,23]. In 2020, the container freight volume along the Yangtze River accounted for more than 60% of the national inland rivers. The development of inland waterway transport means the restructuring of the scale and functions of ports along the Yangtze River, the navigation capacity of the Yangtze waterway, and the industrial layout along the river, leading to changes in the relationship between the development and protection of various resources [24–26], and the issue of sustainable development of ports is becoming important. Resource and environmental issues may arise when port shipping reaches a certain stage of development [27], which also caused various stakeholders to gradually move from conflict to collaboration [28]. Through academic research and practical processes, it is recognized that ecological regulation is a prerequisite for the construction and operation of logistics infrastructure, which can effectively reduce negative environmental externalities [29,30].

As a crucial space carrier of port, port construction is inseparable from the waterfront resource, which is the essential productive factor and most basic component of the port [31], and it has been used as a potential resource for people and developing for hundreds of years for its abundant natural resources that support human life and certain industries [32–34]. For a long time, the waterfront was not mentioned or studied as an independent resource, but it is contained in a large number of coastal zone studies and the protection of resources. With the utilization of marine resources and coastal problems, such as pollution, overexploitation, habitat degradation, and erosion [35–37], integrated coastal zone management (ICZM) was issued as a response. It was implemented through the US

Coastal Zone Management Act, which was promulgated in 1972, and coastal management was given general and worldwide consideration following the publication of UNCED Agenda 21, adopted at the United Nations Conference on Environment and Development in 1992 [38,39]. A large and growing proportion of international studies have been made mainly using the "3S" technology for the extraction and precision evaluation of coastline, the protection and management of waterfronts [40–42], as well as the utilization and revitalization of urban waterfronts [43,44]. As for China, remarkable achievement has been made in developing along the coast and the Yangtze River under the "T"-shaped spatial pattern development policy, making waterfront resources receive ever-higher attention for the vital role which is played in supporting the development of economic axis, especially the Yangtze River Economic Belt [45,46]. The waterfront of the Yangtze River becomes an indispensable part of domestic studies, focusing on the spatial and temporal change, waterfront evaluation, and resource management.

There has been a long-term trend for cities along coasts and rivers to rely on the port to proceed communication globally and bring local economic growth and prosperity [47]. As the vital position of ports is pushing forward the national economy and promoting circulation, the settlement and development of ports are some of the most important socio-economic activities in coastal and riverside zones [48–50]. The utilization of port waterfronts has effectively promoted the economic development of cities and areas, which stimulated the demand of scale expansion, on the contrary, and even promoted the emergence of new ports in the region. In pursuit of transport efficiency and scale economy, many port cities decided to add more terminal capacity and explored more waterfront resources for construction [51], and container ports have become an important support for the development of economy and foreign trade of port cities due to the particularity of the container transportation mode [52]. The ever-larger ships [53], growing shipping traffic [54], and port expansions call for more and more port waterfronts continuously, while the total amount of which are suitable for port utilization is limited and highlighted constantly for their scarcity, as well as their notable value; in the meantime, the land-use and land-cover change in waterfronts can be greatly changed once the port is constructed for the utilization of waterfront resources as carriers, and a high density of anthropogenic activities and land use changes can have significant impacts on the dynamics of both the ecosystem services value and ecosystem functions of the primordial waterfront resource [55–57], while the effectiveness of anthropic interventions for reducing adverse environmental impacts caused by port utilization are considered to be a great challenge [58]. Furthermore, since the 2000s, many initiatives, including "sustainable port", "ecoport", and "green port", have been proposed due to pressure from sustainability issues, port authorities, and organizations, and research institutes have actively undertaken efforts to coordinate the relationship between the development and protection of port waterfront resources. Yet, the studies on the port waterfront take specific ports as research regions in general, and researchers take port waterfronts as research subjects, mainly consisting of the evaluation of suitability [59,60], evaluation of port waterfront utilization patterns [61–63], and valuation [64,65].

Therefore, as the combination and transition zone between water and land, the coastal and riverside zone are considered among the most exploited, inhabited, and threatened areas in the world [66,67] due to the geographic location, making its management a challenge [68]. Effective planning and management are the preconditions for sustainable development [69]. The waterfront is an important part of coastal and riverside regions and resources; scientific management can promote whole area development.

With the wide waterway of the Yangtze River, the Yangtze River Delta (YRD) has an inland port group of the most densely distributed and largest throughputs nationwide. The 12.5 m deep waterway from Nanjing to the Yangtze estuary is completed, meeting the navigation requirements of 50,000-ton seagoing vessels. In 2020, except for Shanghai, the container throughput of inland ports, such as Suzhou, Nantong, Nanjing, and Wuhu, all exceeded 1 million TEU, and the container throughput of the Yangtze mainstream ports in the Yangtze River Delta accounted for nearly 80% of the total container throughput of the

Yangtze mainstream. The rapid development of container shipping began in 2000, and the revitalization of the "golden waterway" and the development of water transportation have become important strategies for national transportation development. After 2010, with the industrial transfer, container transportation has entered more inland areas. In 2015, the Chinese government stepped up conservation of the Yangtze River and stopped its over-development. Reasonable development and protection have become the core issues that various economic activities in the Yangtze River need to explore at present [70]. The port waterfront is the key area for strict management and control to achieve sustainable development. Under the above background, it is urgent to carry out investigation and research on container ports. This paper calculates the waterfront utilization and development trend of container ports in the YRD since 2010 by using high-resolution remote sensing image data and combining relevant information, and it discusses the sustainable development countermeasures of container ports, with a view of providing case support for optimizing the Yangtze River port system and improving the ecological environment protection of the Yangtze River. The first section is the introduction, the second section is the research preparation, the third section is the analysis of the container port waterfront patterns, the fourth section is the enlightenment and countermeasures for the sustainable development of the port waterfront, and the fifth section is the conclusion.

2. Research Preparation

2.1. Research Objectives

This study's core objectives are as follows. First, this paper selects the ports that have participated in container shipping since 2010 by combining high-definition remote sensing images and industrial and commercial information data of port enterprises, and it collects their geographical location, waterfront utilization, and land area width. Secondly, it analyzes the quantity and spatial distribution characteristics of waterfront utilization of container ports since 2010, the relationship between container port and cities, the changes of port external traffic convenience, and the occupation of container port waterfront to ecological reserve. Finally, the paper discusses the enlightenment and countermeasures for the sustainable development of the Yangtze River container port, explains the utilization stage of the port waterfront, judges the changes in the exploitation and protection relationship at different stages, analyses the main causes of the increasing of port waterfront, and puts forward the way to realize the integration of the supply of the container ports and the sustainable utilization of waterfront resources in the Yangtze River (Figure 1).

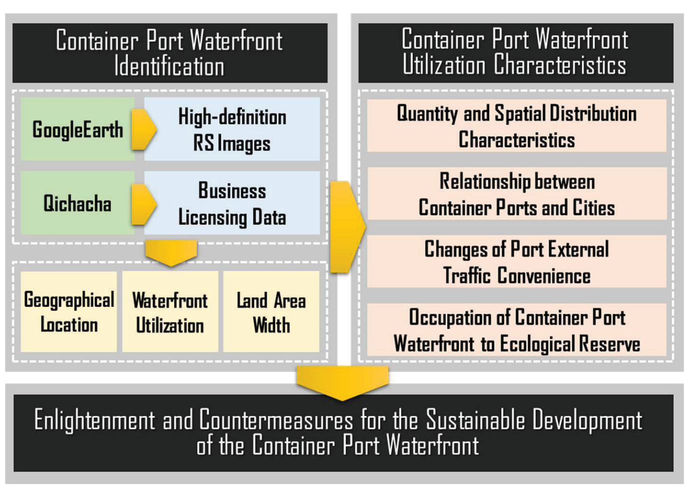

Figure 1. Study framework.

2.2. Methods

2.2.1. Identification of Container Port Waterfront in the Yangtze River

The container port is the general name of the land and water scope of the complete operation of container arrival, loading and unloading to departure, collection, and distribution. Firstly, this paper selects the riverside port enterprises whose business scope includes container operations through the Qichacha (https://www.qcc.com/ accessed on 31 December 2022) enterprise information query system, and it determines the enterprise location through the industrial and commercial registration address and the latest annual report address. On this basis, whether the container operation is actually carried out during the research period is analyzed through high-definition remote sensing images.

In remote sensing images, the port front is a port facility at the junction of land and water, with ship berths and container cranes, mostly designed in a trestle type. The stack yard and the marshalling yard are orderly discharge areas for a large number of containers, with container cranes and on-site transportation vehicles. The freight station also stacks a large number of containers, but unlike the stack yard and the marshalling yard, the loading and unloading of machinery in the freight station is mostly small. Some warehouses are built, and the container stacking is not as neat as the stack yard and the marshalling yard. The specialized container port has a large and tidy container stacking area and a large number of container cranes. The general port is also responsible for the operation of other types of cargo while carrying container transportation. Other cargo can be seen, except containers.

In this paper, 46 ports are selected. For ports that continuously use the waterfront, if they are operated by different owners or different types (specialized or general), we identify them as multiple ports, and the remote sensing image is shown in Figure 2 (sorted from upstream to downstream).

2.2.2. Estimation of Waterfront Pressure in Container Ports

To estimate the container throughput T_{ab} of container port b in city a, take the container operation capacity of each port in one city as the same level, and divide the container throughput of the city according to the proportion of each port to the length of total container port waterfronts of the city.

$$T_{ab} = T_a \cdot \frac{w_{ab}}{w_a} \quad (1)$$

where T_a is the total port container throughput of city a, w_{ab} is the length of waterfront of container port b in city a, and w_a is the total length of the city's container port waterfront.

2.3. Data Sources

This paper selects 14 port cities in the Yangtze River Delta, including Shanghai, Suzhou, Nantong, Wuxi, Taizhou, Changzhou, Yangzhou, Zhenjiang, Nanjing, Maanshan, Wuhu, Tongling, Chizhou, and Anqing, which have port container operations and liner routes in the mainstream of the Yangtze River, as seen in the research samples.

The waterfront utilization data were extracted from the high-resolution remote sensing images of the mainstream of the Yangtze River in 2010, 2014, 2018, and 2022 using the method of 2.2. Enterprise. Business data come from Qchacha (https://www.qcc.com/), an official enterprise credit inquiry system registered by the national enterprise credit inquiry system, which can provide enterprise addresses and business scope. The high-definition remote sensing image data of the mainstream of the Yangtze River are obtained through Google Earth Pro. We download and import the data into ArcGIS software for further operations, collecting the geographical location of container ports, waterfront utilization, and land area width. Ports where container operations are included in the business scope, but cannot be reflected in remote sensing images, are not included in the study. The data of ecological reserves are derived from the General Plan for the Protection and Utilization of the Waterfront of the Yangtze River Economic Belt, prepared by the Yangtze River Water Conservancy Commission in 2016.

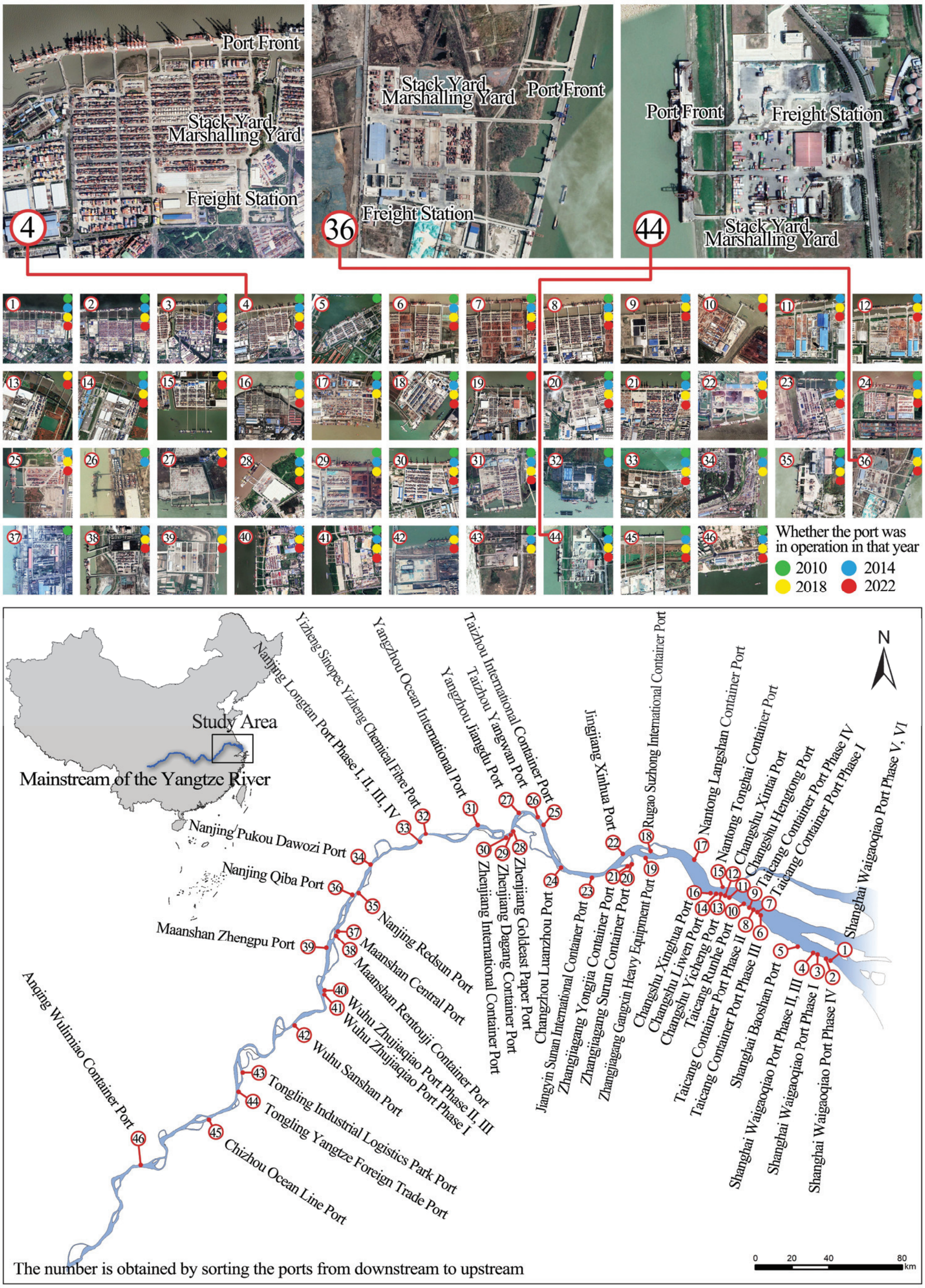

Figure 2. Identification of the container port waterfront.

3. Characteristics and Patterns of Container Port Waterfronts Utilization

3.1. The Length of Container Port Waterfronts Increases, and There Are Dense Areas Attached to Big Cities

In the Yangtze River Delta, the number of container ports and the utilization of the waterfronts have increased significantly along the Yangtze River (Figure 3a). The total length of container port waterfronts has increased from 22.5 km in 2010 to 33.1 km in 2018, and it decreased to 32.4 km in 2022. The number of container ports has increased from 31 in 2010 to 41 in 2018, and it decreased to 38 in 2022. Due to differences in economic development and port and shipping infrastructures, the exploitation and utilization of container port waterfronts are different between provinces and cities. The utilization of container port waterfronts in Jiangsu is the highest in the YRD, from 12.1 km in 2010 to more than 20 km in 2018, accounting for more than 60% of the total since 2014. The utilization of container port waterfronts in Anhui is small, but the growth rate is fast, from 2.5 km in 2010 to 4.9 km in 2022. Even if the average annual growth rate is 5.8%, it is still less than 1/4 of Jiangsu.

At the urban level, the utilization of container port waterfronts is generally decreasing from downstream to upstream, and it forms a dense zone attached to central cities and major manufacturing bases (Figure 2) to match the expansion of the global production-sale network and to serve trade circulation. Shanghai and Suzhou, located in the Yangtze River estuary, have a large scale of container port waterfronts utilization, of which Suzhou has continued to grow, and it has surpassed Shanghai. In Shanghai, there are strict restrictions on the total amount of productive waterfronts and port construction land and the environmental protection of the Yangtze River estuary, and the hydrological and geological suitability of port construction in the estuary areas is poor. It is popular to use Suzhou as a port of release for Shanghai to alleviate the burden of regional container shipping. A dense zone of container ports is formed between Shanghai Waigaoqiao and Suzhou Changshu (Sutong Bridge), which is a hub area for international liner docking and river–sea intermodal transportation. In the middle of the lower reaches of the Yangtze River, Nanjing is the shipping center of the lower reaches, and Wuhu is the shipping center of Anhui. They undertake regional container distribution and intermodal transport functions. The number of container ports and the scale of waterfront utilization are high, forming another relatively small, dense zone. Nanjing is the largest container port waterfront utilization, except Shanghai and Suzhou, reaching 4.5 km in 2018, and the container port waterfronts utilization in Wuhu has exceeded 3 km in 2022, 1.7 times the total number of other four port cities along the Yangtze River in Anhui.

Ports with higher waterfronts utilization are mostly located in the shipping center cities and the lower reaches, mostly in the dense zones (Figure 3b). The waterfront length of the main container ports in Shanghai, Suzhou (Zhangjiagang, Taicang, Changshu), and Nanjing, is more than 1000 m. In Anhui, only in Wuhu, there is a trend of large-scale ports. The demand for Anhui's own container shipping is low, and the high cost of opening up the port and the rear land area has a restraining effect. Suzhou Taicang Container Port (Phase I, II, III, IV), Shanghai Waigaoqiao Port (Phase I, II, III, and Phase IV, V, VI), Nanjing Longtan Port (Phase I, II, III, IV), and Wuhu Zhujiaqiao Port (Phase I, II, III), which cumulatively utilize the waterfronts, all exceed 2000 m.

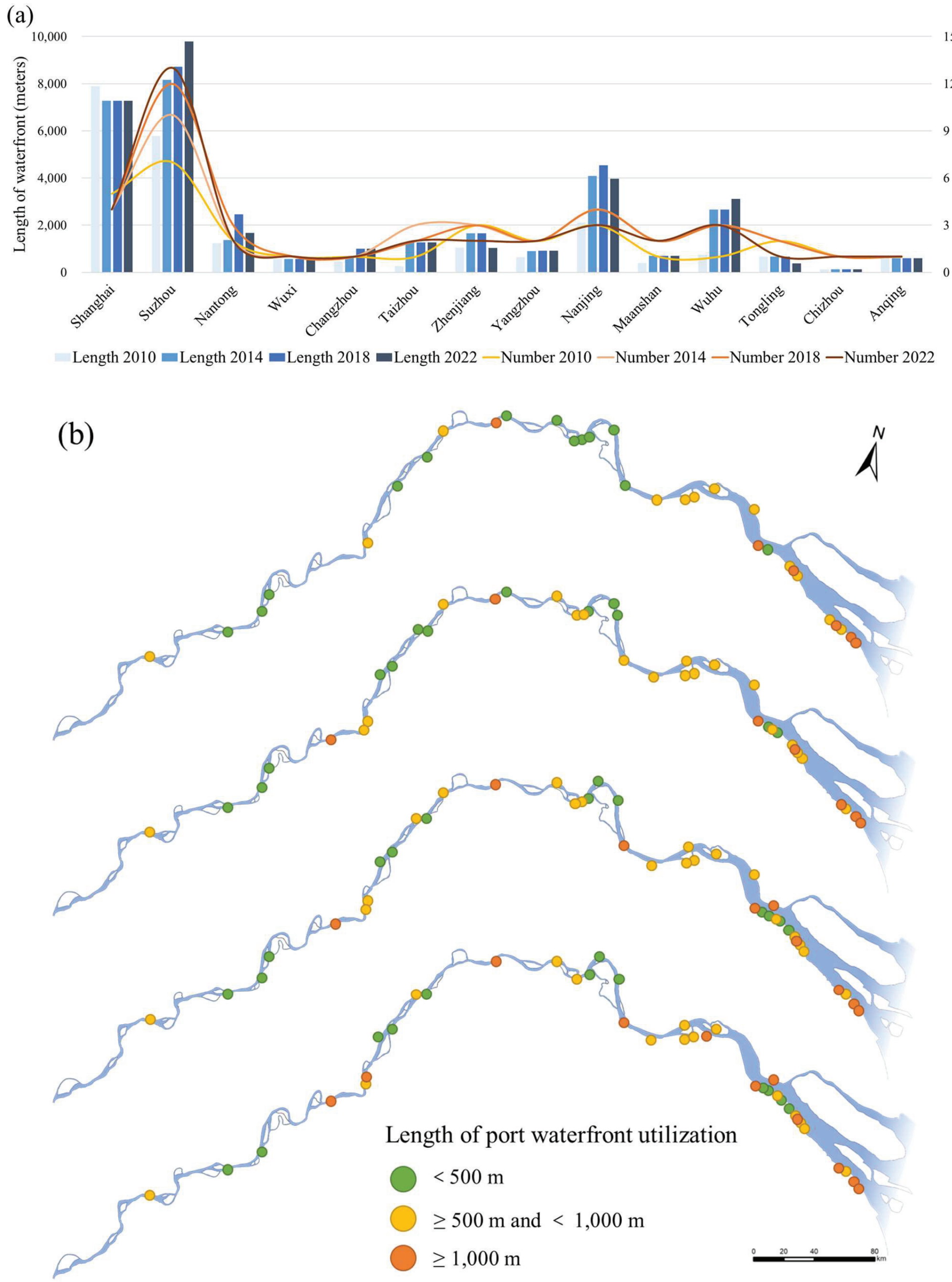

Figure 3. Distribution of Yangtze container ports and length of their waterfronts' utilization in the Yangtze River Delta. (**a**) the number of container ports and the length of waterfront utilization in cities, (**b**) distribution of container port waterfronts.

3.2. The Development Direction of Container Ports Is Large-Scale and Specialized

Large and specialized container ports can use supporting facilities to improve the transport efficiency to centralize the cargo receipt and delivery and transform the traditional port from the extension of the upstream and downstream of the waterfront to the extension of the rear land area behind the waterfront, so as to realize the intensive use of the waterfront and reduce the fragmentation of the riverside landscape. The length of the waterfront used by one port has grown rapidly. The average length has increased from 725.2 m in 2010 to 851.5 m in 2022, and the average width of the land area used has increased from 702.8 m to 772.3 m. Compare the ports according to the three types of using waterfront below 500 m, 500–1000 m (excluding 1000 m), 1000 m, and above. The proportion of ports using higher waterfronts continues to increase, and the proportion of ports using 500 m and above increases by 10%. The number of smaller container ports with waterfronts of less than 500 m decreased from 13 in 2010 to 12 in 2022. The average width of land area they use is small. The number of medium-sized ports with waterfronts of 500–1000 m increased from 12 in 2010 to 19 in 2014, and it decreased to 15 in 2022. The average width of land area they use is medium. The number of large ports with waterfronts of 1000 m and above increased from six in 2010 to 11 in 2022. The average width of land area they use is the largest, with an average of 942.6 m–1149.8 m in four years (Figure 4a).

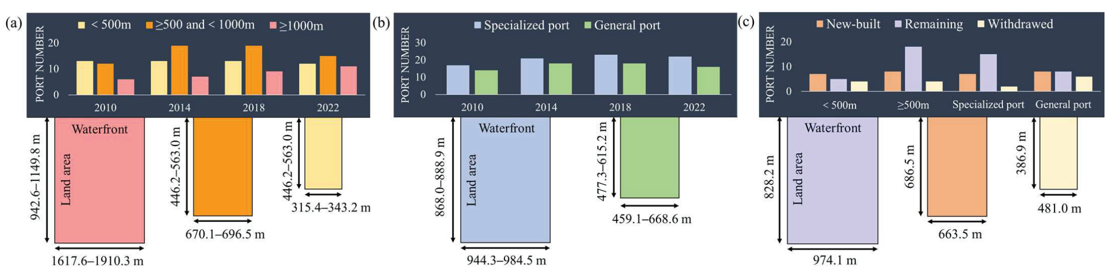

Figure 4. Difference in waterfront length and land area width in different ports. (**a**) number of ports with different waterfront length level and average waterfront length and land area width, (**b**) number of ports with different port function type and average waterfront length and land area width, (**c**) number of ports with different port operation states and average waterfront length and land area width.

The construction cost and site selection requirements of specialized container ports are high, so some general ports participate. In the early stage, due to the small scale of container transportation, some port cities did not build specialized ports. The number of specialized ports increased from 17 in 2010 to 23 in 2018, and it decreased to 22 in 2022. The number of general ports increased from 14 in 2010 to 18 in 2014 and 2018, and it decreased to 16 in 2022. The main port areas and public ports in various cities are mostly specialized ones, while some non-core peripheral ports and cargo owners' ports are mostly general ones. The average length of specialized ports is close to 1000 m, between 953.5 m–984.5 m in four years, and its land area width is used between 868.0 m–886.5 m. Compared with that, the average length of general ports in 2022 is only 668.6 m, and the land area width is 615.2 m (Figure 4b).

The container ports are divided into new-built, withdrawn, and remaining. The remaining ports carried out container operations during the study period, the new-built ports joined the container operations during the study period, and the withdrawn ports are no longer carrying out container operations during the study period due to various reasons. The decrease in ports is mainly small, and the increase is mainly large and medium-sized. After the optimization and adjustment of the port system, eight ports, including four small and four medium ones, have been removed or changed for container operation, which cannot meet the modern transportation standards. The average waterfront utilization is 481.0 m, and the average land area width is 386.9 m. Among them, two specialized ports are Nantong Langshan Container Port and Shanghai Baoshan Port. There are 15 new-built ports, including seven small and eight large- or medium-sized ones. The average waterfront utilization is 663.5 m, and the average land area width is 686.5 m. Among them, there are seven specialized ports. High-standard construction of specialized ports has become an important step for cities to develop container shipping, and this is supplemented by some small and medium-sized ports to improve the availability of transportation and to relieve the pressure of large port areas. There are 23 remaining ports, including five small ones and 18 large- or medium-sized ones. The average waterfront utilization is 974.1 m, and the average land area width is 828.2 m. Some ports can meet the needs of waterway shipping development and the environmental protection requirements of the Yangtze River. Most of them are the main port areas of each city, and the waterfront utilization increases gradually due to the phased planning and construction. Through the reservation, it will be extended after the upgrading of the logistics services and popularization of containerization. The Changzhou Luanzhou port increased from 450 m to 1000 m, and the Wuhu Zhujiaqiao port Phase II and III increased from 800 m to 1265 m (Figure 4c).

3.3. The Utilization of Container Port Waterfront Is Approaching the Periphery of the City and Areas with Convenient Transportation

The development of container ports and the utilization of waterfronts are gradually moving away from urban areas to expand. During the study period, the average straight-line distance from the container ports to the city center increased from 16.5 km to 19.4 km, the average driving distance increased from 21.8 km to 25.7 km, and the average driving time increased from 35.9 min to 39.7 min. The number of ports with straight-line distance of no less than 20 km has increased from 12 to 20, and the average length of a waterfront is 902.2–948.8 m, while the average length of a waterfront with a straight-line distance of less than 20 km is 613.4–750.7 m. The number of ports with driving distance of no less than 20 km has increased from 18 to 26, and the average length of waterfront is 903.4–949.8 m, while the average length of a waterfront with a driving distance of less than 20 km is 478.3–638.4 m (Figure 5a, Table 1). External transportation is an important link in port construction, matching each port with the nearest expressway entrance. The average driving distance between the two reduced from 10.6 km in 2010 to 7.0 km in 2022, the average driving time reduced from 17.5 min to 12.3 min, and the number of ports less than 10 km from the entrance increased from 16 to 28, accounting for 51.6% to 73.7% of the total. Many ports have opened entrances through new dedicated lines or expressways passing through the port area to reduce the complexity of the main entrance of expressways connecting with urban internal and external passenger transport. The number of ports sharing the entrance with the urban area decreased from 16 to 5, and the proportion decreased from 51.6% to 13.2% (Figure 5b,c, Table 1).

Many cities have built ports in peripheral areas to reduce the use of ports in urban areas. The average distance and driving time from the new-built ports to the city center is relatively long, while the average distance and driving time from the withdrawn ports is relatively short. Newly built ports with straight-line distance and driving distance of no less than 20 km accounted for 66.7% and 73.3% respectively, compared to 25.0% and 37.5% of the withdrawn ones and 43.5% and 65.2% of the remaining ones (Figure 4a). The average distance and driving time from newly built and remaining ports to the nearest expressway entrance is relatively short, while the average distance and driving time from withdrawn ports is relatively long. The average driving distance from the newly built and remaining ports to the nearest expressway entrance is 7.8 km and 6.5 km, respectively, and the average driving time is 13.9 min and 11.3 min, respectively, which is far lower than the 12.15 km and 20.3 min from the withdrawn port. The proportion of the withdrawn ports and the urban traffic flow sharing the entrance are 87.5%, The newly built and remaining ones are only 6.7% and 17.4%, respectively (Figure 5b,c, Table 1).

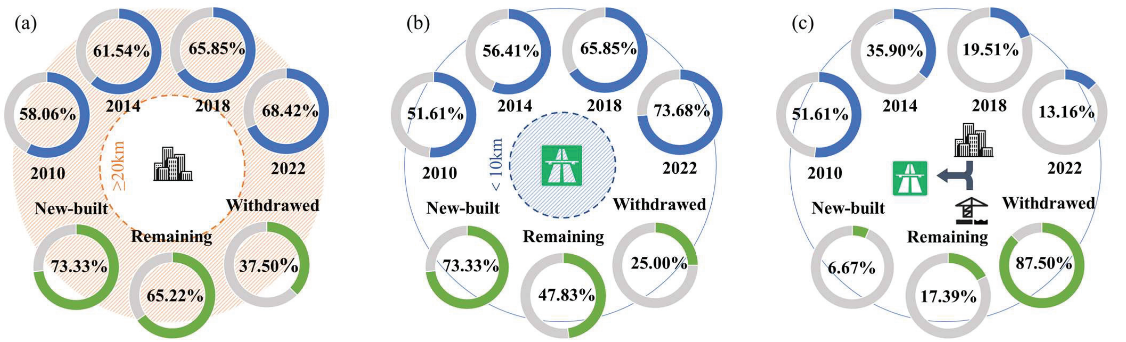

Figure 5. The proportion of ports more than 20 km away from the city center, less than 10 km away from nearest expressway entrance, and the nearest expressway entrance shared with cities. (**a**) the proportion of ports in different years and different states more than 20 km away from the city center, (**b**) the proportion of ports in different years and different states less than 10 km away from nearest expressway entrance, (**c**) the proportion of nearest expressway entrance shared by ports and cities.

Table 1. The distance between the container ports and the city center and the nearest expressway entrance.

	2010	2014	2018	2022	New-Built	Remaining	Withdrawed
Average straight-line distance to the city center (km)	16.5	17.5	18.6	19.4	21.5	18.1	12.1
Average driving distance to the city center (km)	21.8	23.3	24.9	25.7	29.1	23.4	16.7
Average driving time to the city center (min)	35.9	37.8	39.3	39.7	43.3	37.3	30.3
Average driving distance to the nearest expressway entrance (km)	10.6	9.5	7.9	7	7.8	6.5	12.2
Average driving time to the nearest expressway entrance (min)	17.5	16.4	14.2	12.3	13.9	11.3	20.3

The relationship between the ports and the cities is gradually expanding, and the convenience of the port external transportation is improving. There is incompatibility between the utilization of port waterfront and urban leisure and recreation as the main functional types of waterfronts. Transport pollution limits the improvement of urban quality and the living environment, and it cuts the landscape along the river in the city. At the same time, the waterfront utilization that focuses on urban living limits the expansion of the port area and the construction of collection and distribution channels, which promotes the outward migration of some ports. During the study period, the waterfront utilization of newly built ports is generally far from the urban area, but there are still a few ports, such as Tongling, Anqing, and Wuxi (Jiangyin), close to the main city.

3.4. The Container Port Waterfronts Occupy the Ecological Reserve and Is Highly Concentrated

According to the General Plan for the Protection and Utilization of the Waterfront of the Yangtze River Economic Belt, the container port waterfronts occupy the ecological reserve in the YRD, and the occupation length is expanding with the development of the inland waterway transport. The length of the ecological reserve section occupied by ports increased from 6167 m in 2010 to 11,125 m in 2018, and then it decreased to 10,265 m in 2022. The total proportion increased from 27.4% to 33.6%, and then it decreased to 31.7%. The number of ports increased from 11 in 2010 to 19 in 2018, and then it decreased to 17 in 2022, and the total proportion increased from 35.5% to 46.3%, and then it decreased to 44.7%. The annual growth of the conflict length in 2010–2014 was 9.3%, From 2015 to 2018, the annual growth rate was 6.1%. After 2018, the relationship between the container ports and the protection reserve eased, and the scale of conflict decreased. The core area of the reserve is an important area to play the protection function, and the occupied length has increased from 3637 m to 7630 m, and the proportion has increased from 59.0% to 74.3% (Figure 6a).

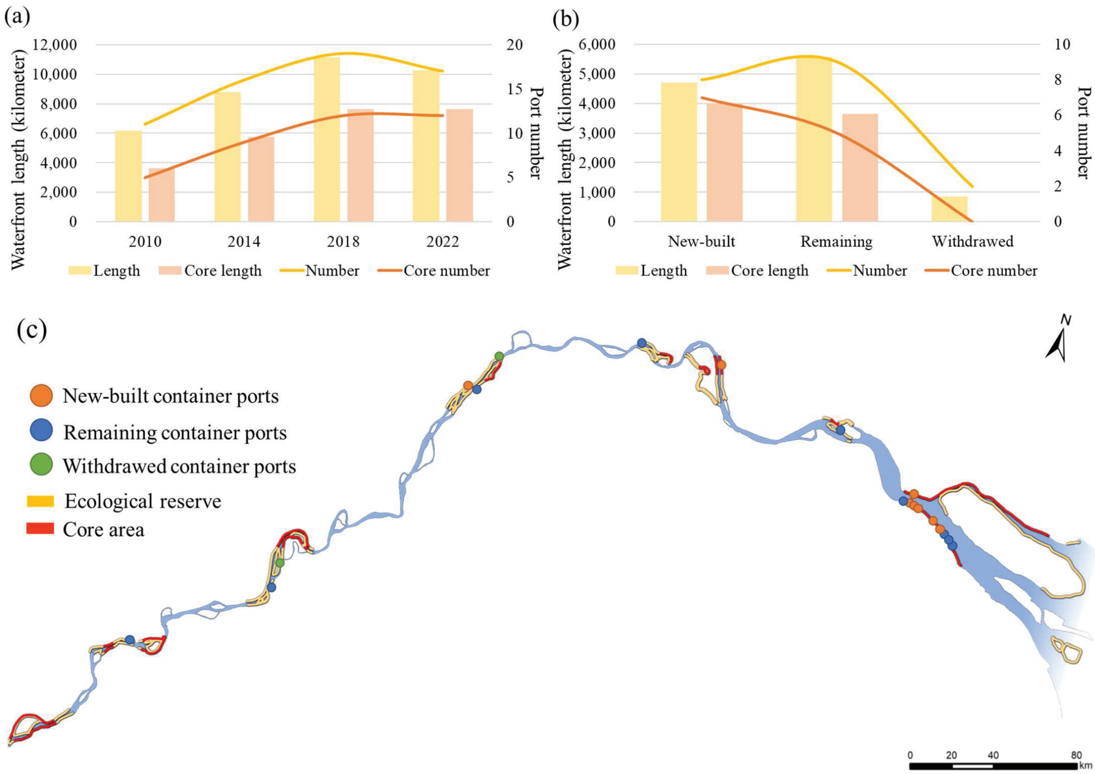

Figure 6. Conflicts between container port waterfront and protection reserve. (**a**) length of ecological reserve occupied by container ports, (**b**) length of ecological reserve occupied by container ports in different states, (**c**) distribution of ecological reserve occupied by container ports.

The conflicts are mainly distributed in the Yangtze River estuary, Nanjing, and Tongling. Almost all waterfronts in the Yangtze River estuary area are within the scope of protection. This section is the core area of the National Aquatic Germplasm Resources Protection Area of Yangtze Coilia, which has led to a large number of ports in Suzhou (Taicang, Changshu) and Nantong, falling within the protection area, forming a large-scale occupation. The number of ports in this area has increased from 4 to 10, accounting for 36.4% to 58.8% of all conflict ports, and the occupied waterfront has increased from 3059 m to 6572 m. The proportion increased from 49.6% to 64.0%. The main city of Nanjing and its upstream areas are all in the National Aquatic Germplasm Resources Protection Zone of Leiocassis longirostris in Dashengguan, and a large number of waterfronts of Tongling are in the National Nature Reserve of Freshwater Dolphin (Figure 6c).

Different from the traditional cognition of the newly built and remaining ports evading reserve, the scale and proportion of the reserve are high. There are eight newly built ports in the reserve, occupying 4703 m of the protected waterfront, accounting for 53.3% and 47.3% of the number of ports and the length of waterfront utilization. There are nine remaining ports in the reserve, occupying 22,404 m of the protected waterfront, accounting for 39.1% and 24.8% of the number of ports and the length of waterfront utilization. The core area of the reserve is occupied by seven newly built and five remaining ports, with the occupied length of 3993 m and 3637 m, respectively, accounting for 84.9% and 65.4% of the total occupation of each type. The average length of conflicting ports is small, and the proportion of specialized and large ports is low. Their impact on the environment is large, so the site selection is more cautious (Figure 6b).

4. Enlightenments and Countermeasures for the Sustainable Development

4.1. Transformation of Productive Waterfront Utilization Has Reshaped the Sustainable Development Pattern along the Yangtze River

Development activities can directly change the natural background of the waterfront and its surroundings, as the waterfront is a disposable one-time, non-renewable resource. Ports' site selection, which is the joint result of the hinterland economy, waterfront ecological environment, distribution facilities, etc., relates to the economic development stages and resource development mode. For most of the Yangtze River ports, waterfront utilization develops in three periods, exploitation, conflict, and mitigation, as it relates to their long history and intensive human activities.

Inland container shipping develops with the expansion of global product sales in inland regions. This speed-developing mode and traditional shipping both work. Waterfront utilization of traditional shipping is horizontal expansion-based, in which the capacity relates to the length of the shoreline. It results in the heavy utilization of the waterfront and threats to ecological preservation areas and drinking water sources. In contrast, inland container shipping reduces unit transport costs and pollutant emissions by transferring the land transport and increasing the proportion of multimodal transport to river–ocean combined transport. Container shipping is away from heavy waterfront utilization, as it possesses high operational efficiency with the standardized transport and centralized feeder ports distributed in the YRD, which are the logistic nodes sited in the inland region during the port regionalization process. Hence, for the Yangtze valley, the container shipping need of a whole city can be realized in hundreds of meters of waterfront, and the same is the case in the Rhine Valley. It has only been decades since container shipping developed in the Yangtze River. In the 1980s, Shanghai began to develop container shipping and gradually expanded to Suzhou (Taicang, Changshu, and Zhangjiagang) in the Yangtze River estuary. In the 1990s, it became popular in the Jiangsu Province. Later, in 2000, large-scale container operations began in Anhui Province. With the construction of −12.5 m and −10.5 m deep waterway in the lower reaches of the Yangtze River, container throughput has the fastest growth among all kinds of cargo.

The development of container ports is closely related to China's foreign trade growth and the Yangtze River's resources and environmental management. In 2010, the period wherein China was the "world factory", container shipping developed rapidly in the entire region, with the fastest-growing foreign trade. To alleviate the pressure of collection and distribution, some existing wharves were altered for larger transport capacity and the most use of the waterfront. During the conflict period, many container ports were located in the old port area, and lack of pollutant collection and material supplements caused many environmental problems.

"Mitigation" is considered to begin after 2015. We believe that there are two reasons. One is regulation. The decades of urbanization and industrialization along the Yangtze River have accumulated a series of resource and environmental issues [21,71]. The Chinese government has proposed a national strategy of "Yangtze River Protection" to guide the sustainable use of the waterfront of ports. After meeting current and future transportation needs, ports are not allowed to be constructed excessively. Scholars have reviewed the challenges faced by current inland port and shipping [72] and believe that sustainable development requires social, economic, and environmental aspects, such as environmental measures, setting up emission control zones, using clean energy [73,74], and more efficient ship scheduling systems [75].

On the other hand, by establishing a modern transportation and supply chain covering the Yangtze River basin, one can integrate logistic links to reduce the resource and environmental impact of unit transportation and to internalize external costs. Specialized public container ports have been built in various regions, and intensive utilization of waterfront resources is taking shape. With the continuous improvement of environmental control requirements, the external costs of various modes of transportation, especially roads and railways, continue to rise. Under the same environmental control standards, inland waterway transport has the smallest cost consumption [76,77]. Inland ports can alleviate traffic congestion and reduce transportation costs in seaport cities [18,78]. When ships stay in the seaport for a long time, it can cause environmental impact on residents of seaport cities. In this process, intermodal transport plays an important role. Through the optimization and improvement of the logistics system in infrastructure docking, regulatory procedures, as well as other aspects, as well as various transportation links, have formed service models that can integrate regional logistics [79,80], significantly reducing the social marginal cost of transportation. For the additional economic burden caused by ecological measures, suppliers provide cost compensation through cooperation and various technologies.

4.2. Conflicts between Waterfront Utilization and Protection Are Inevitable, and It Is Necessary to Face Up to the Rise in the Occupation of Protected Areas

Although the container ports in the Yangtze River Delta account for only 1% of the total waterfront, some protected waterfront covers nearly 100 km. Many waterfronts in some cities are in protected areas due to highly unevenly distributed protection needs. For Suzhou, Nanjing, Tongling, and other cities, a large number of waterfronts is within the protection reserve. Besides, many cities along the Yangtze River, including Nantong, Nanjing, and Wuhu, try to amplify the riverside economic and social benefits by constructing urban corridors with location advantages. Local governments tend to construct gardens to exert the multi-function of the riverside landscape, as the Yangtze River is attractive to residents. Hence, many waterfronts are used for leisure and recreation. The dilemma in container ports' site selection makes the local stakeholders develop waterfronts for economic development pressure in the game between economic development and resource protection. The productive activities of the waterfront cannot be prohibited, so there will be conflicts between port development and waterfront protection.

Inland waterway container transport is an important means to solve China's logistic development dilemma. The proportion of national total logistic expenses in relation to GDP has decreased from 17.37% in 2010 to 16.00% in 2015, but it is still higher than that of developed countries, and there is still a certain distance from the world average of 10–15%. Assuming that logistics efficiency can be raised to a level close to that of the United States (5–7%), it can save nearly 5 trillion yuan per year. Most of the logistics costs come from the process of transporting goods from inland regions to coastal ports. Although the length of domestic transportation is shorter than that of international section, the cost accounts for a high proportion of the total freight. This has provided a huge market capacity and development space for inland water transportation. The cost of inland container transportation with shipping as the core is 50% of road transportation. It is marked by standardized transportation units, achieving high efficiency and informatization, as well as changing traditional cargo source organization and transportation processes. "Door to door" transportation [81,82] can reduce the turnaround time of various links in the transportation process [83], accelerating the diversification of the relationship between ports and hinterland and the process of port regionalization.

The shift from land transportation to water transportation occurs under environmental control. Among the main transportation modes, the energy consumption and pollutant emissions per unit of cargo transportation by waterways are far lower than those by highways, which can reduce costs by nearly 10% and greenhouse gas emissions by more than 15% [84]. The European Commission proposed the Marco Polo Plan at the beginning of the 21st century, aiming to transform land freight into other greener modes. The two phases of the Marco Polo plan ultimately reduced carbon dioxide emissions by 4.36 million tons, reduce land freight turnover by 64 billion kilometers, and reduce truck queuing by 64,000 km. After 2010, the EU further promoted the development of sustainable transport modes, with the goal of reducing greenhouse gas emissions by more than 60% by 2050.

The volume of container ports that conflict with the protection reserve is considerable, increasing from 2.99 million TEU in 2010 to 7.16 million TEU in 2020. Considering the unit waterfront container handling capacity of each container port in the city at the same level, it is calculated according to the method in Section 2.1. and accounting for 8.2% of the inland river container throughput in the Yangtze River Delta to 12.2%. In 2022, all of the container operations of Maanshan, Anqing, and Nantong, and 60% of Suzhou and Yangzhou, were in protected areas. In the Yangtze River estuary, Suzhou and Nantong have become the two most critical relocating regions of Shanghai, and Taicang Port Area has the largest container port group on the Yangtze River, except Shanghai. These are all related to Shanghai's lacking waterfront, scarce land resources, and continuous increase in collecting and distributing pressure. Although protection is essential, the considerable container operation over several millions will conflict with the protection zone no matter where they are distributed, as all of the waterfronts of this section are in the protection zone. If there is no room for container shipping, it will seriously affect the construction of the integrated logistics system and social-economic development, locally, or even in a larger region. At this stage, the best time to adopt the most stringent protection measures and overall relocation has yet to be noticed. Considering many large-scale hub ports exist in the protection reserve, the primary way is to develop these ports and carry out ecological compensation and restoration through other methods simultaneously.

The sustainable use of the port waterfront is a dynamic process. By improving the entry and exit mechanism of the port waterfront, the utilization efficiency of the port waterfront can be improved, and the supply of the waterfront can be shifted to large-scale public ports with high throughput capacity per unit waterfront. Besides, it is also helpful in promoting the gradual withdrawal of ports with low unit waterfront handling capacity or long waterfronts occupied by ports. These ports are relatively expensive due to modernization. In port construction, many methods are beneficial, following the green concept from the whole life cycle of design, construction, and operation, including restoring the intertidal zone, establishing ecological corridors, setting up aquatic animal and plant habitats, building ecological security barriers and water exchange spaces, and providing environmental compensation and pollution control fees for nearby residents.

4.3. Through the Horizontal Coordination of the Port Groups along the River, Balance the Waterfront Load of All Container Ports

In the sustainable utilization of the waterfront, the increase in terminals gradually slows down while the demand for container transport continuously grows. To share the pressure of partial urban ports on waterfront, it is necessary to build a cross-city and cross-province integrated port logistics system in the YRD port group through operation and management, cargo source organization, barge calls, and multimodal transport. Considering the unit container handling capacity of the waterfront within a city at the same level, the waterfront loads of ports vary significantly between cities. On the one hand, the pressure on the waterfront of hub cities is relatively high. The Shanghai International Shipping Center ranks the highest in the YRD, reaching 3000 TEU/m in 2022, while the neighboring Suzhou is relatively less stressful. Therefore, the port cooperation between Shanghai and Suzhou can effectively reduce the pressure of container handling and the resources and environmental burden. It can also optimize the security and connectivity of the shipping network through the new port hub. The SIPG (Shanghai International Port (Group)) has invested in the SZP (Suzhou Port) and many container enterprises in Suzhou. Nanjing, Yangtze River Shipping Center, is under high pressure in the middle of the YRD, and Wuhu, Anhui Shipping Center, is stressful in Anhui Province. On the other hand, non-hub cities are transited to specialized ports of the new port area, from small/medium-sized and general ports. The change in waterfront suppliant is slower than the spurting growth of container transport capacity. The waterfront pressure of container ports in Nantong and Wuxi is 1100 TEU/m and 1000 TEU/m in 2022, respectively. Tongling, Maanshan, Chizhou, and Anqing in 2022 are twice that of 2010, of which Anqing is 8.22 times compared with 2010 (Figure 7).

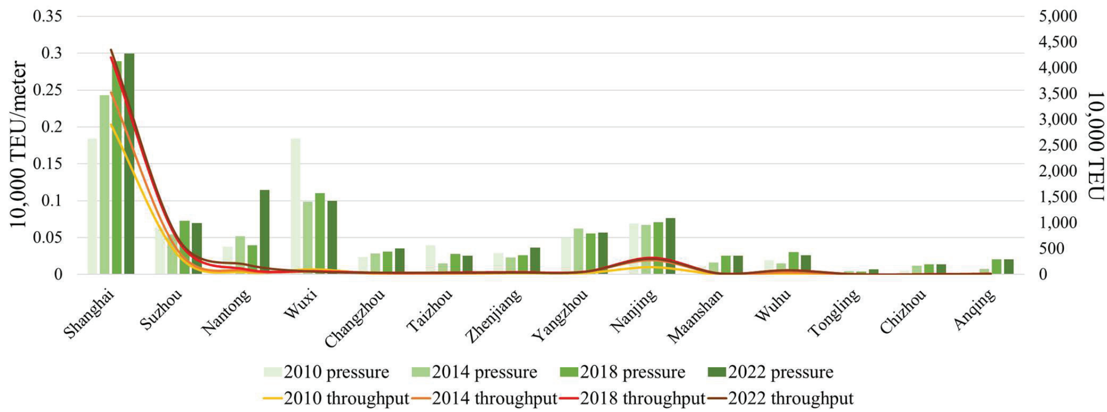

Figure 7. Container port waterfront pressure and container throughputs.

Hub cities are the core of container port waterfront supply. Although urban expansion and resource and environmental constraints have further squeezed the living space of the port waterfront, the limited waterfront and land use will be inclined at the national and provincial levels. It will also take inland waterway shipping and container intermodal transport as an important part of future development. Shanghai Waigaoqiao, Nanjing Longtan, and Wuhu Zhujiaqiao are still in expansion. Non-hub cities are not major in shipping. The pressure on the shipping volume and routes increased considerably during the study period. The excessive development of the port waterfront leads to resource waste, and inactive development puts serious pressure on collection and distribution. Some local governments and practitioners need to pay more attention to the planning of the container port system and investment in specialized and large-scale ports.

Therefore, researchers and governments should focus on integrated port cities, shifting from hub ones. A cross-city comprehensive port and shipping logistics system is expected when there is a bottleneck in the hub area, using the resources of the surrounding cities. Some practices on co-construction and sharing transport infrastructure that break administrative boundaries are shown. The non-hub port areas' container transport pressure is relatively high, especially as more cities join the container shipping system. Shipping will transfer the original non-container transport to container transport and the original overland transport to inland waterway transport. Practitioners in these cities must adapt to container shipping, including proficiency in operating rules and procedures and matching infrastructure. The waterfront supply of container ports can help these cities form shipping interfaces for the inland container and close the gap with the first-mover cities.

4.4. There Are Barriers between Higher and Lower Levels or between Different Departments and Cities, Which Can Be Solved by the Yangtze River Delta Integration Mechanism

After going through the process from "conflict" to "mitigation", the relationship between the development and utilization of port waterfront and people's life, resource management, and environmental protection will eventually move towards "coordination". At present, container port waterfront management involves many government departments, such as development and reform, water conservancy, natural resources, transportation, agriculture, ecological environment, etc. As the corresponding performance assessment is divided into various departments, relevant departments have issued policies and institutions from their respective functions, with weak connectivity and relevance, as well as a lack of cross-department overall management at the Yangtze River Delta level, and many problems of waterfront resource development and protection are difficult to coordinate in a unified manner. The development, reform, water conservancy, and natural resource departments play prominent roles. The development and reform departments pay attention to the layout of industries and infrastructure along the river and hold the right of approval. The water conservancy departments have the right of waterfront, river management, and related approval. The natural resources departments pay attention to the standardization of natural resources protection and land use along the river and constrain the port construction and operation process through land space planning and ecological red line protection.

The change in the status of departments in the government has affected the direction of shoreline development and protection. The waterfront and industrial transportation planning along the Yangtze River were led by the development and reform department. After 2020, the management of the Yangtze River waterfront was transferred to the water conservancy department. This department focused on water intake protection, flood control, and drainage facilities' layout while weakening the rationality and predictability of the port layout. At the same time, the natural resources department mastered the dominant power of the national spatial planning, and the red line control thinking was enlarged, and the strong position of the department requires other plans and policies to match it, and some waterfronts cannot be fully utilized. The management and approval of the use of land and water areas are not in the same department, and some of the water areas behind the port are planned for other use types, and vice versa. With the further release of the shipping potential of the Yangtze River, the demand for port waterfront resources is still relatively strong. Some deep-water waterfronts are located within the scope of the reserve and cannot carry out production activities, and some of the rear land areas are not suitable for large-scale exploitation and construction, or the cost is high, which makes the high-quality waterfront resources increasingly tense, especially in Nanjing, Suzhou, and Zhenjiang.

With the implementation of the Yangtze River protection strategy, the riverside industries have gradually withdrawn from the waterfronts, and ports have become one of the few productive waterfront types on the Yangtze River that are still in continuous supply. It is necessary to improve the comprehensive management system of the waterfront with multiple departments and administrative regions to ensure the waterfront supply of key projects. On the basis of total amount control of waterfront utilization, and to strengthen the connection between waterfront planning and other plans, use the hinterland of the waterfront to reduce the occupation of riverside space, releasing it for port use.

5. Conclusions

Based on the summary of remote sensing images and relevant data, this paper calculates the waterfront utilization of the container ports along the Yangtze River in the YRD, analyzes the waterfront organization pattern and change characteristics, and puts forward the enlightenment and countermeasures for the sustainable development of the port waterfronts. The academic contribution of this paper was to analyze the waterfront utilization of inland container ports by combining remote sensing image data and enterprise data, as well as to expand the research of port resources from coastal to inland areas. In addition, this paper puts forward suggestions for sustainable development in view of problems existing in the Yangtze River, which has practical significance for the development of Yangtze River Shipping, exploitation, and protection of land resources along the Yangtze River.

In the YRD, the waterfront utilization of container ports has increased along the Yangtze River, showing a decreasing from downstream to upward, and it has formed dense zones attached to the central cities and major manufacturing bases. The ports with higher length of waterfront are mostly located in the shipping central cities and the Yangtze

River estuary. The development direction of container ports is large-scale and specialized. The number of large ports with waterfront utilization of 1000 m and above has increased from six to eleven, and the number of specialized ports has increased from 17 to 23. The utilization of container port waterfront is approaching the periphery of the city and areas with convenient transportation. The utilization of container port shoreline will be close to the periphery of the city and convenient transportation areas. The number of ports with driving distance of no less than 20 km from the city center increased from 18 to 26, and the number of ports with driving distance of less than 10 km from the nearest expressway entrance increased from 16 to 28. The container port waterfronts occupy the ecological reserve, and the conflicts are expanding with the development of shipping, mainly distributed in the Yangtze River estuary, Nanjing, and Tongling.

Based on the empirical analysis, this paper puts forward four enlightenments. First, the exploitation and utilization of the port waterfront has experienced multiple stages of "utilization—conflict—mitigation". With the transformation of productive waterfront utilization, the pattern of sustainable development along the Yangtze River has changed. Secondly, the conflict between waterfront utilization and protection is inevitable. The traffic volume of ports in conflict with the reserve has reached a considerable scale. It is necessary to face up to the temporary rapid rise of encroachment on the reserve. Third, through the horizontal coordination of the port system along the river, the original focus on the hub cities will be transferred to the comprehensive consideration of the port cities in the whole region, and the waterfront load of different types of container ports can be balanced. Fourth, use the Yangtze River Delta integration system and mechanism to solve the barriers between higher and lower levels or between different departments and regions.

In further research, on the one hand, by collecting more remote sensing images and historical documents, the research time can be extended to the 1990s, and the research area can be extended to the middle and upper reaches of the Yangtze River to build a more complete waterfront and land use database of ports. On the other hand, through surveys of some waterfront sections and port enterprises, it is possible to further study the relationship between waterfront utilization and protection and its driving mechanisms, especially the challenges faced by ecological service functions, the impact of port and shipping technology changes on waterfront resources and environment [2], to comb the evolution of the interactive relationship between waterfront development, to explore the port carrying capacity, to explore economic development, and to explore the issue of the transfer of externalities of inland port shipping [72].

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